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THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

PROCEEDINGS

MID-NOVEMBER, 1906

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IS DEVOTED EXCLUSIVELY TO THE PRESIDENTIAL ADDRESS

"ON THE ART OF CUTTING METALS"

BY MR. F. W. TAYLOR

TO BE DELIVERED ON TUESDAY EVENING, DECEMBER 4, AT 8.45 O'CLOCK. THE DISCUSSION OF THE PAPER WILL TAKE PLACE AT THE SESSION TO BE HELD THE FOLLOWING MORNING, WEDNESDAY, DECEMBER 5, AT 9.30 O'CLOCK

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ON THE ART OF CUTTING METALS

By FRED W. TAYLOR, PHILADELPHIA
Member of the Society

Part 1

For Index and Definitions, see end of Part 1

1 The experiments described in this paper were undertaken to obtain a part of the information necessary to establish in a machine shop our system of management, the central idea of which is:

2 (A) To give each workman each day in advance a definite task, with detailed written instructions, and an exact time allowance for each element of the work.

3 (B) To pay extraordinarily high wages to those who perform their tasks in the allotted time, and ordinary wages to those who take more than their time allowance.

4 There are three questions which must be answered each day in every machine shop by every machinist who is running a metal-cutting machine, such as a lathe, planer, drill press, milling machine, etc., namely:

a What tool shall I use?

b What cutting speed shall I use?

c What feed shall I use?

5 Our investigations, which were started 26 years ago with the definite purpose of finding the true answer to these questions under all the varying conditions of machine shop practice have been carried on up to the present time with this as the main object still in view.

6 The writer will confine himself almost exclusively to an attempted solution of this problem as it affects "roughing work"; *i. e.*, the preparation of the forgings or casting for the final finishing cut, which is taken only in those cases where great accuracy or high finish is called for. Fine finishing cuts will not be dealt with. Our principal object will be to describe the fundamental laws and principles which will enable us to do "roughing work" in the shortest time, whether the cuts are light or heavy, whether the work is rigid or elastic, and

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whether the machine tools are light and of small driving power or heavy and rigid with ample driving power.

7 In other words, our problem is to take the work and machines as we find them in a machine shop, and by properly changing the countershaft speeds, equipping the shop with tools of the best quality and shapes, and then making a slide rule for each machine to enable an intelligent mechanic with the aid of these slide rules to tell each workman how to do each piece of work in the quickest time.

8 It is to be distinctly understood that this is not a vague, Utopian result, to be hoped for in the future, but that it is an accomplished fact, and has been the daily practice in our machine shops for several years; and that the three great questions, as to shape of tools, speed, and feed, above referred to, are daily answered for all of the men in each shop far better by our one trained mechanic with the aid of his slide rule than they were formerly by the many machinists, each one of whom ran his own machine, etc., to suit his foreman or himself.

9 It may seem strange to say that a slide rule enables a good mechanic to double the output of a machine which has been run, for example, for ten years by a first-class machinist having exceptional knowledge of and experience with his machine, and who has been using his best judgment. Yet, our observation shows that, on the average, this understates the fact.

10 To make the reason for this more clear it should be understood that the man with the aid of his slide rule is called upon to determine the effect which each of the twelve elements or variables given below has upon the choice of cutting speed and feed; and it will be evident that the mechanic, expert or mathematician does not live who, without the aid of a slide rule or its equivalent, can hold in his head these twelve variables and measure their joint effect upon the problem.

11 These twelve elements or variables are as follows:

a the quality of the metal which is to be cut;
b the diameter of the work:
c the depth of the cut;
d the thickness of the shaving;
e the elasticity of the work and of the tool;
f the shape or contour of the cutting edge of the tool, together with its clearance and lip angles;
g the chemical composition of the steel from which the tool is made, and the heat treatment of the tool;
h whether a copious stream of water, or other cooling medium, is used on the tool;
j the duration of the cut; *i. e.*, the time which a tool must last under pressure of the shaving without being reground;

k the pressure of the chip or shaving upon the tool;
l the changes of speed and feed possible in the lathe;
m the pulling and feeding power of the lathe.

12 Broadly speaking, the problem of studying the effect of each of the above variables upon the cutting speed and of making this study practically useful, may be divided into four sections as follows:

13 (A) The determination by a series of experiments of the important facts or laws connected with the art of cutting metals.

14 (B) The finding of mathematical expressions for these laws which are so simple as to be suited to daily use.

15 (C) The investigation of the limitations and possibilities of metal cutting machines.

16 (D) The development of an instrument (a slide rule) which embodies, on the one hand, the laws of cutting metals, and on the other, the possibilities and limitations of the particular lathe or planer, etc., to which it applies and which can be used by a machinist without mathematical training to quickly indicate in each case the speed and feed which will do the work quickest and best.

17 In the fall of 1880, the machinists in the small machine shop of the Midvale Steel Company, Philadelphia, most of whom were working on piecework in machining locomotive tires, car axles, and miscellaneous forgings, had combined to do only a certain number of pieces per day on each type of work. The writer, who was the newly appointed foreman of the shop, realized that it was possible for the men to do in all cases much more work per day than they were accomplishing. He found, however, that his efforts to get the men to increase their output were blocked by the fact that his knowledge of just what combination of depth of cut, feed and cutting speed would in each case do the work in the shortest time, was much less accurate than that of the machinists who were combined against him. His conviction that the men were not doing half as much as they should do, however, was so strong that he obtained the permission of the management to make a series of experiments to investigate the laws of cutting metals with a view to obtaining a knowledge at least equal to that of the combined machinists who were under him. He expected that these experiments would last not longer than six months.

18 With the exception of a few comparatively short periods, however, these experiments have continued until the present time, through a term of about 26 years.

19 The writer wishes to call attention to the fact that in these first experiments he was far more fortunate than almost all of the experimenters who have investigated the subject since then, in

having at his disposal a comparatively large mass of uniform metal to work upon, and a comparatively large and powerful machine to work with, a 66-inch diameter boring mill and large locomotive tires made of hard tire steel of uniform quality having been used. He was also especially fortunate in having over him as president of the company, Mr. William Sellers, who, as is well known, was one of the most patient and broad-minded experimenters of his day. Mr. Sellers, in spite of the protests which were made against the continuation of this work, allowed the experiments to proceed; even, at first, at a very considerable inconvenience and loss to the shop. The extent of this inconvenience will be appreciated when it is understood that we were using a 66-inch diameter vertical boring mill, belt-driven by the usual cone pulleys, and that in order to regulate the exact cutting speed of the tool, it was necessary to slow down the speed of the engine that drove all of the shafting in the shop; a special adjustable engine governor having been bought for this purpose. For over two years the whole shop was inconvenienced in this way, by having the speed of its main line of shafting greatly varied, not only from day to day but from hour to hour. Before the two years had elasped, however, the writer had obtained such valuable and unexpected results from the experiments as to much more than justify all of the annoyance and expenditure, and soon after that he readily obtained permission to employ a young technical graduate to devote his whole time to the continuation of this work.

20 Mr. G. M. Sinclair, a graduate of Stevens Institute of Technology, devoted his entire time to this work from 1884 to 1887, when he left the employ of the company.

21 Mr. H. L. Gantt, also a graduate of Stevens Institute succeeded Mr. Sinclair in July, 1887, and has been interested with us in carrying on these experiments throughout their whole period.

22 In 1898 Mr. Maunsel White, of Bethlehem, another graduate of Stevens Institute, joined us and has been actively interested in our work up to this time.

23 Mr. Carl G. Barth, a graduate of The Technical School of Horten, Norway, joined us in 1899, and is still actively working on our investigations.

24 During these years we have consulted so freely together in all matters relating to these experiments that with few exceptions hardly a step has been taken which can be said to have originated with any one man. Therefore, whatever credit or blame may come to this work should be impartially divided among us. In writing this paper, then, no effort will be made to discriminate, as to the results which

have been obtained in our investigations, between the work of one man and another.

25 Mr. White is undoubtedly a much more accomplished metallurgist than any of the rest of us; Mr. Gantt is a better all-round manager, and the writer of this paper has perhaps thefaculty of holding on tighter with his teeth than any of the others. It should be said, however, that Mr. Barth, who is a very much better mathematician than any of the rest of us, has devoted a large part of his time during the last years of these experiments to carrying on the mathematical work along the lines laid out, and that without his special ability and untiring energy our progress would have been much slower, indeed it is doubtful whether we should have ever reached the present solution of the problem without his aid.

26 In addition to the five men who have mainly directed and carried on this work, the writer wishes to acknowledge the most loyal and efficient aid and coöperation of many others who have assisted in the actual running of the machines and in recording or tabulating the data. Among these, he would particularly mention Mr. Dwight V. Merrick, Mr. D. C. Fenner, Mr. James Kellogg, Mr. Sidney Newbold, Mr. Joseph Welden. Mr. N. W. Wickersham, Mr. Edward Kneisley, and Mr. Leonard G. Backstrom.

27 Our experiments were continued in the works of the Midvale Steel Company until 1889, when the writer left their employ. Since then, these investigations have been carried on in various shops and at the expense of different companies. Among these, we would especially acknowledge our indebtedness to the Cramp's Shipbuilding Company, Messrs. Wm. Sellers & Co., the Link-Belt Engineering Company, Messrs. Dodge & Day, and, more than all, to the Bethlehem Steel Company.

28 In carrying on this work more than ten machines have been fitted up at various times with special driving apparatus and the other needed appliances, all machines used since 1894 having been equipped with electric drives, so as to obtain any desired cutting speed. The thoroughness with which the work has been done may perhaps be better appreciated when it is understood that we have made between thirty and fifty thousand recorded experiments, and many others of which no record was kept. In studying these laws we have cut up into chips with our experimental tools more than 800,000 pounds of steel and iron. More than sixteen thousand experiments were recorded in the Bethlehem Steel Company. We estimate that up to date between $150,000 and $200,000 have been spent upon this work, and it is a very great satisfaction to feel that those whose generosity has enabled

us to carry on the experiments have received ample return for their money through the increased output and the economy in running their shops which have resulted from our experiments.

29 Throughout the whole 26 years we have succeeded in keeping almost all of these laws secret, and in fact since 1889 this has been our means of obtaining the money needed to carry on the work. We have never sold any information connected with this art for cash, but we have given to one company after another all of the data and conclusions arrived at through our experiments in consideration for the opportunity of still further continuing our work. In one shop after another machines have been fitted up for our use, workmen furnished us to run them, and especially prepared tools, forgings and castings supplied in exchange for the data which we had obtained to date; and we have the best indication that they received full value for the money spent from the fact that the same company fitted up for us at intervals of several years three sets of apparatus, the additional knowledge obtained each time evidently warranting them in making the added outlay.

30 During this period all of the companies who were given this information, and all of the men who worked upon the experiments, were bound by promises to the writer not to give any of this information away nor to allow it to be published. Most of these promises were verbal; and in this day when there is so much talk about dishonesty and graft in connection with some of our corporations and prominent business men, it is a notable fact that through a period of 26 years it has not come to our knowledge that any one of the many men or companies connected with this work has broken a promise. The writer has his doubts whether any other country can produce a parallel record of such widespread good faith among its engineers and mechanics.

31 It seems to us that the time has now come for the engineering fraternity to have the results of our work, in spite of the fact that this will cut off our former means of financing the experiments. However, we are in hopes that the money required to complete this work may be obtained from some other source.

32 The writer has no doubt that many of the discoveries and conclusions which mark the progress of this work have been and are well known to other engineers, and we do not record them with any certainty that we were the first to discover or formulate them, but merely to indicate some of the landmarks in the development of our own experiments, which to us were new and of value. The following is a record of some of our more important steps:

33 (A) In 1881, the discovery that a round-nosed tool could be run under given conditions at a much higher cutting speed and therefore turn out much more work than the old-fashioned diamond-pointed tool.

34 (B) In 1881, the demonstration that, broadly speaking, the use of coarse feeds accompanied by their necessarily slow cutting speeds would do more work than fine feeds with their accompanying high speeds.

35 (C) In 1883, the discovery that a heavy stream of water poured directly upon the chip at the point where it is being removed from the steel forging by the tool, would permit an increase in cutting speed, and, therefore, in the amount of work done of from 30 to 40 per cent. In 1884, a new machine shop was built for the Midvale Steel Works, in the construction of which this discovery played a most important part; each machine being set in a wrought iron pan in which was collected the water (supersaturated with carbonate of soda to prevent rusting), which was thrown in a heavy stream upon the tool for the purpose of cooling it. The water from each of these pans was carried through suitable drain pipes beneath the floor to a central well from which it was pumped to an overhead tank from which a system of supply pipes led to each machine. Up to that time, so far as the writer knows, the use of water for cooling tools was confined to small cans or tanks from which only a minute stream was allowed to trickle upon the tool and the work, more for the purpose of obtaining a water finish on the work than with the object of cooling the tool; and, in fact, these small streams of water are utterly inadequate for the latter purpose. So far as the writer knows, in spite of the fact that the shops of the Midvale Steel Works until recently have been open to the public since 1884 no other shop in this country was similarly fitted up until that of the Bethlehem Steel Company in 1899, with the one exception of a small steel works which was an offshoot in personnel from the Midvale Steel Company.

36 (D) In 1883, the completion of a set of experiments with round nosed tools; first, with varying thicknesses of feed when the depth of the cut was maintained constant; and, second, with varying depths of cut while the feed remained constant, to determine the effect of these two elements on the cutting speed.

37 (E) In 1883, the demonstration of the fact that the longer a tool is called upon to work continuously under pressure of a shaving, the slower must be the cutting speed, and the exact determination of the effect of the duration of the cut upon the cutting speed.

38 (F) In 1883, the development of formulæ which gave mathema-

tical expression to the two broad laws above referred to. Fortunately these formulæ were of the type capable of logarithmic expression and therefore suited to the gradual mathematical development extending through a long period of years, which resulted in making our slide rules, and solved the whole problem in 1901.

39 (G) In 1883, the experimental determination of the pressure upon the tool required on steel tires to remove cuts of varying depths and thickness of shaving.

40 (H) In 1883, the starting of a set of experiments on belting described in a paper published in Transactions, Vol. 15 (1894).

41 (J) In 1883, the measurement of the power required to feed a round-nosed tool with varying depths of cut and thickness of shaving when cutting a steel tire. This experiment showed that a VERY DULL TOOL required as much pressure to feed it as to drive the cut. This was one of the most important discoveries made by us, and as a result all steel cutting machines purchased since that time by the Midvale Steel Company have been supplied with feeding power equal to their driving power and very greatly in excess of that used on standard machine tools.

42 (K) In 1884, the design of an automatic grinder for grinding tools in lots and the construction of a tool room for storing and issuing tools ready ground to the men.

43 (L) From 1885 to 1889, the making of a series of practical tables for a number of machines in the shops of the Midvale Steel Company, by the aid of which it was possible to give definite tasks each day to the machinists who were running machines, and which resulted in a great increase in their output.

44 (M) In 1886, the demonstration that the thickness of the chip or layer of metal removed by the tool has a much greater effect upon the cutting speed than any other element, and the practical use of this knowledge in making and putting into everyday use in our shops a series of broad-nosed cutting tools which enabled us to run with a coarse feed at as high a speed as had been before attained with round-nosed tools when using a fine feed, thus substituting, for a considerable portion of the work, COARSE FEEDS AND HIGH SPEEDS for our old maxim of COARSE FEEDS AND SLOW SPEEDS.

45 (N) In 1894 and 1895, the discovery that a greater proportional gain could be made in cutting soft metals through the use of tools made from self-hardening steels than in cutting hard metals, the gain made by the use of self-hardening tools over tempered tools in cutting soft cast iron being almost 90 per cent, whereas the gain in cutting hard steels or hard cast iron was only about 45 per cent. Up to this

time, the use of Mushet and other self-hardening tools had been almost exclusively confined to cutting hard metals, a few tools made of Mushet steel being kept on hand in every shop for special use on hard castings or forgings which could not be cut by the tempered tools. This experiment resulted in substituting self-hardening tools for tempered tools for all "roughing work" throughout the machine shop.

46 (P) In 1894 and 1895, the discovery that in cutting wrought iron or steel a heavy stream of water thrown upon the shaving at the nose of the tool produced a gain in cutting speed of SELF-HARDENING TOOLS of about 33 per cent. Up to this time the makers of self-hardening steel had warned users never to use water on the tools.

47 (Q) From 1898 to 1900, the discovery and development of the Taylor-White process of treating tools; namely, the discovery that tools made from chromium-tungsten steels when heated to the melting point would do from two to four times as much work as other tools.

48 (R) In 1899-1902, the development of our slide rules, which are so simple that they enable an ordinary workman to make practical and rapid everyday use in the shop of all the laws and formulæ deduced from our experiments.

49 (S) In 1906, the discovery that a heavy stream of water poured directly upon the chip at the point where it is being removed from CAST IRON by the tool would permit an increase in cutting speed, and therefore, in the amount of work done, of 16 per cent.

50 (T) In 1906, the discovery that by adding a small quantity of vanadium to tool steel to be used for making modern high speed chromium-tungsten tools heated to near the melting point, the hardness and endurance of tools, as well as their cutting speeds, are materially improved.

51 While many of the results of these experiments are both interesting and valuable, we regard as of by far the greatest value that portion of our experiments and of our mathematical work which has resulted in the development of the slide rules; *i. e.*, the patient investigation and mathematical expression of the exact effect upon the cutting speed of such elements as the shape of the cutting edge of the tool, the thickness of the shaving, the depth of the cut, the quality of the metal being cut and the duration of the cut, etc. This work enables us to fix a daily task with a definite time allowance for each workman who is running a machine tool, and to pay the men a bonus for rapid work.

52 The gain from these slide rules is far greater than that of all the other improvements combined, because it accomplishes the original object, for which in 1880 the experiments were started; *i. e.*, that of taking the control of the machine shop out of the hands of the many

workmen, and placing it completely in the hands of the management, thus superseding "rule of thumb" by scientific control.

53 By far the most difficult and illusive portion of this work has been the mathematical side: first, finding simple formulæ which expressed with approximate accuracy the effect of each of the numer ous variables upon the cutting speed; and, second, finding a rapid method of using these formulæ in the solution of the daily machine shop problems. Several times during the progress of this mathematical work, the writer, feeling himself completely baffled, has asked the expert assistance of some of the best mathematicians in the country. They all smiled when told that we expected to solve mathematically a problem containing *twelve variables*, and in each case, after keeping the formulæ before them for a longer or shorter time, returned the problem to the writer with the statement that it belonged distinctly in the realm of "rule of thumb" or empiricism, and could be solved only by the slow method of trial and error.

54 In the investigation of an art such as that of cutting metals, and about which at the time our work was started there was so little scientific knowledge, two types of experiments are possible.

55 First, the thoroughly scientific type, in which, after an analysis of all the variable elements which affect the final result, an attempt is made to hold all of the elements constant and uniform, except the one variable which is under investigation, and this one is systematically changed and its effect upon the problem carefully noted.

56 It is to this type that our experiments belong, thanks mainly to the fact that Mr. William Sellers (one of the most scientific experimenters of his day) was president of the Midvale Steel Company when the writer started his work.

57 Second, the type of experiments in which the effect of two or more variables upon the problem is investigated at the same time and in the same experiment.

58 This method is of course much quicker than the thoroughly scientific type, and it is largely for this reason, in the opinion of the writer, that almost all of the other experimenters in this field have chosen it. Several of the experiments of this type have proved most valuable and developed much useful information, and it is with hesitancy that the writer criticises the work of any of these experimenters, since he appreciates most keenly the difficulties under which they worked, and is grateful for the information contributed by them to the art. After much consideration, however, he has decided to point out what he believes to be a few errors made by these experimenters, with the same object which he has in indicating our own

false steps: namely, that of warning future investigators against similar errors.

59 Almost the whole course of our experiments is marked by imperfections in our methods, which, as we have realized them, have led us to go again more carefully over the ground previously traveled. These errors may be divided into three principal classes:

60 (A) The adoption of wrong or inadequate standards for measuring the effect of each of the variables upon the cutting speed.

61 (B) Failure on our part from various causes to hold all of the variables constant except the one which was being systematically changed in order to study the effect of these changes upon the cutting speed.

62 (C) The omission either through oversight or carelessness on our part of some one of the precautions which should be taken to insure accuracy, or failure to record some of the phenomena considered unimportant at the time, but which afterward proved to be essential to a complete understanding of the facts.

63 In the second portion of this paper will be given in detail a statement of the appliances, methods and principles which we believe to be necessary to use in order to obtain reliable results. For the purpose of a more general discussion of the subject, however, it seems important to anticipate this portion of the paper by describing in detail the standard which we have finally adopted as a true criterion for determining the effect of each of the variables upon the cutting speed.

64 The effect of each variable upon the problem is best determined by finding the exact rate of cutting speed (say, in feet per minute) which shall cause the tool to be completely ruined after having been run for 20 minutes under uniform conditions.

65 For example, if we wish to investigate the effect which a change in the thickness of the feed has upon the cutting speed, it is necessary to make a number of tools which are in all respects uniform, as to the exact shape of their cutting edge, their clearance and lip angles, their chemical composition and their heat treatment. These tools must then be run one after another, each for a period of 20 minutes, throughout which time the cutting speed is maintained exactly uniform. Each tool should be run at a little faster cutting speed than its predecessor, until that cutting speed has been found which will cause the tool to be completely ruined at the end of 20 minutes (with an allowance of a minute or two each side of the 20-minute mark). In this way that cutting speed is found which corresponds to the particular thickness of shaving which is under investigation.

66 A change is then made in the thickness of the shaving, and another set of 20-minute runs is made, with a series of similar uniform tools, until the cutting speed corresponding to the new thickness of feed has been determined; and by continuing in this way all of the cutting speeds are found which correspond to the various changes of feed. In the meantime, every precaution must be taken to maintain uniform all the other elements or variables which affect the cutting speed, such as the depth of the cut and the quality of the metal being cut; and the rate of the cutting speed must be frequently tested during each 20-minute run to be sure that it is uniform.

67 The cutting speeds corresponding to varying feeds are then plotted as points upon a curve, and a mathematical expression is found which represents the law of the effect of feed upon cutting speed. We believe that this standard or method of procedure constitutes the very foundation of successful investigation in this art; and it is from this standpoint that we propose to criticise both our own experiments and those made by other investigators.

68 It was only after about 14 years' work that we found that the best measure for the value of a tool lay in the exact cutting speed at which it was completely ruined at the end of 20 minutes. In the meantime, we had made one set of experiments after another as we successively found the errors due to our earlier standards, and realized and remedied the defects in our apparatus and methods; and we have now arrived at the interesting though rather humiliating conclusion that with our present knowledge of methods and apparatus, it would be entirely practicable to obtain through four or five years of experimenting all of the information which we have spent 26 years in getting.

69 The following are some of the more important errors made by us:

70 We wasted much time by testing tools for a shorter cutting period than 20 minutes, and then having found that tools which were apparently uniform in all respects gave most erratic results (particularly in cutting steel) when run for a shorter period than 20 minutes; we erred in the other direction by running our tools for periods of 30 or 40 minutes each, and in this way used up in each single experiment so much of the forging that it was impossible to make enough experiments in cutting metal of uniform quality to get conclusive results. We finally settled on a run of 20 minutes as being the best all-round criterion, and have seen no reason for modifying this conclusion up to date.

71 We next thought a proper criterion for judging the effect of a

given element upon the cutting speed lay in determining the particular cutting speed which would just cause a tool to be slightly discolored below the cutting edge at the end of the 20 minutes. After wasting six months in experimenting with this as our standard, we found that it was not a true measure; and then adopted as a criterion a certain definite dulling or rubbing away of the cutting edge. Later it was found, however, that each thickness of feed had corresponding to it a certain degree of dullness or injury to the cutting edge at which point regrinding was necessary (the thicker the shaving the duller the tool should be before grinding); and a third series of experiments was made with this as a standard. While experimenting on light forging a standard dullness of tool was used which was just sufficient to push the forging and tool apart and so slightly alter the diameter of the work. All of these criterions were discarded, however, when in 1894 we finally hit upon the true standard, above described, of completely ruining the tool in 20 minutes.

72 As will be pointed out later in the paper, this standard demands both a very large and expensive machine to experiment with, and also large, heavy masses of metal to work upon, which is unfortunate; but we believe without apparatus and methods of this kind it is out of the question to accurately determine the laws which are sought.

73 Experiments upon the art of cutting metals (at least those experiments which have been recorded) have been mainly undertaken by scientific men, mostly by professors. It is but natural that the scientific man should lean toward experiments which require the use of apparatus and that type of scientific observation which is beyond the scope of the ordinary mechanic, or even of engineers unless they have been especially trained in this kind of observation. It is perhaps for this reason more than any other that in this art several of those elements which are of the greatest importance have received no attention from experimenters, while far less fruitful although more complicated elements, have been the subject of extended experiments.

74 As an illustration of this fact we would call attention to two of the most simple of all of the elements which have been left entirely untouched by all experimenters, namely:

a the effect of cooling the tool through pouring a heavy stream of water upon it, which results in a gain of 40 per cent in cutting speed;

b the effect of the contour or outline of the cutting edge of the tool upon the cutting speed, which when properly designed results in an equally large percentage of gain.

75 Both of these elements can be investigated at comparatively small cost, and with comparatively simple apparatus, while that element which has received chief attention from experimenters, namely, the pressure of the chip on the tool, calls for elaborate and expensive apparatus and is almost barren of useful results.

76 This should be a warning to all men proposing to make experiments in any field, first, to look thoroughly over the whole field, and, at least, carefully consider all of the elements from which any practical results may be expected; and then to select the more simple and elementary of these and properly investigate them before engaging in the more complicated work.

77 The most notable experiments in this art that have come to the writer's attention are those made at Manchester, England, during the years 1902 and 1903. All these experiments were made jointly by eight of the most prominent English manufacturing companies, among whom were Armstrong, Whitworth & Co.; Vickers' Sons & Maxim, John Brown & Co., Thomas Firth & Sons, and others, who combined with the Manchester Association of Engineers and the Manchester Municipal School of Technology, the latter being principally represented by Dr. J. T. Nicolson, who made the final report entitled "Experiments with a Lathe Tool Dynamometer," published in Transactions, Vol. 25.

78 In 1901, a committee of the Verein Deutscher Ingenieure (Union of German Engineers), together with the managers of some of the larger engineering works in Berlin, made an interesting series of experiments which was published September 28, 1901, in the "Zeitschrift des Verein Deutscher Ingenieure," and in November 15, 1905, there were published in Bulletin No. 2 of the University of Illinois, experiments made by Prof. L. P. Breckinridge and Henry B. Dirks.

79 The work of all these men belongs to the second type of experiments above referred to, in which the joint effect of two or more variables is studied at the same time. In the case of the Manchester experiments, the work appears to have been, to a considerable extent, a test as to the all-round knowledge in the art of cutting metals possessed by eight of the prominent English firms. These firms each presented tools made from their own tool steel, treated their own way, and ground to whatever shapes and angles the particular company considered would do the largest amount of work. Each company was allowed to have one guess on each of the qualities of metal worked upon, with each change of feed and depth of cut, as to the cutting speed at which they believed their tool would do the most work. If, under this cutting speed, the tool failed to hold out

throughout the stipulated period of time, they were then given no opportunity to find the exact cutting speed at which the tool would do its best work. And, on the other hand, in those cases in which a tool did good work throughout its specified period of time, no effort was made to find how much faster it could have run and still do good work.

80 A glance at Plates 13, 14 and 15 at the end of Dr. Nicolson's report shows the great variety in the shapes of the tools used in the experiments. Yet no effort was made to definitely determine which make of tool steel or which shape of the tool was best, or even in case a tool did exceptionally good work, no effort was made to determine whether this was due to the shape of the tool or to the quality and treatment of the tool steel.

81 As was to be expected from any such test, each one of the eight companies repeatedly made guesses as to the proper speeds for their tools to run which were very wide of the mark. Yet in spite of this, it is notable that in each case some one of the eight firms guessed fairly close to the proper cutting speed, so that by selecting the best of these various guesses Dr. Nicolson, in writing the report, gives a very valuable and interesting table on p. 250 of the Manchester Report, summarizing the best speeds attained in cutting the soft, medium and hard steels, and the soft, medium and hard cast irons experimented on, in each case with four combined changes of depth of cut and thickness of feed.

82 This table conclusively proves the practical value of experiments of this nature, even when carried on in a thoroughly unscientific manner. There is, however, one element in these experiments which was very carefully investigated, and the results of which are of general scientific value; namely, the determination of the pressure of the chip or shaving upon the nose of the tool.

83 That the conclusions reached as to pressure are of value is due to the fact that upon this particular element, neither the shape of the tool nor the composition or treatment of the tool has very great effect, and in each case the pressure of the chip upon the tool appears to have been carefully observed and tabulated, so that experiments which are valueless from a scientific standpoint for most of the elements, confirm substantially, as to the pressure of the chip on the tool, the results of some of our previous experiments on this element.

84 The writer has a great respect for Dr. Nicolson as an experimenter, as his later work in this field has shown him to be a thoroughly scientific investigator; but feels it necessary to call attention to an error which even he has fallen into, namely, that of attempting to

deduce a formula for the cutting of metals from a summary of the Manchester and German experiments. These experiments, from a scientific standpoint, were so defective as to make it out of the question to deduce formulæ, because no effort was made to keep the following variables uniform: (1) the shape of the cutting edge and the lip and clearance angles of the tool varied from one experiment to another; (2) the quality of the tool steel varied; (3) the treatment of the tool varied; (4) the depth of the cut varied from that aimed at; (5) the cutting speed was not accurately determined at which each tool would do its maximum work throughout a given period of time; and (6) in reading the report of these experiments it does not appear that any careful tests were made to determine whether each of the various forgings and castings experimented on was sufficiently uniform throughout in quality to render the tests made upon them of scientific value. The same criticism, broadly speaking, applies to both the German and the University of Illinois experiments.

85 In fact, in none of these sets of experiments have they appreciated the necessity of MEASURING SEPARATELY the effect produced upon the cutting speed of two of the most important elements in the problem, (*a*) the thickness of the feed, and (*b*) the depth of the cut. In all of these investigations and in formulæ given by Dr. Nicolson on p. 249 of the Manchester report, as well as in a formula published by him in "Technics," for January, 1904, summarizing the results of the Manchester and German experiments, the area of the cut "a" is used as though it were a single variable, whereas the sectional area of the shaving is, in fact, the product of the depth of the cut multiplied by the feed. The fact is, however, that the thickness of the shaving or the feed has a greater effect upon the cutting speed than any other element, while the depth of the cut has only a comparatively small effect. When this is realized, it becomes apparent that any formula or even any data containing the area of the cut (or shaving) as a single element is valueless from a scientific standpoint. To illustrate: a cut which is $\frac{1}{2}$ inch deep with $\frac{1}{32}$ inch feed has the same sectional area as a $\frac{1}{8}$ inch depth cut by $\frac{1}{8}$ inch feed; namely, $\frac{1}{64}$ inch sectional area. Our experiments show that if a cutting speed for a $\frac{1}{8}$ inch by $\frac{1}{8}$ inch cut were 10 feet per minute, then the cutting speed for a $\frac{1}{2}$ inch by $\frac{1}{32}$ inch cut would be 18 feet per minute. From which the impossibility of using the area of the cut as an element in a formula is apparent.

86 Broadly speaking, it is unwise to draw conclusions and make formulæ from experiments in which more than one variable is allowed to vary in the same trial. This criticism is made in no sense to

belittle the value of the work done by others, but with the object to pointedly call the attention of future experimenters to such errors as have been made primarily by ourselves and also by others.

87 The results obtained by Dr. Nicolson from the Manchester experiments led him to make another set of experiments for the purpose of determining accurately the pressure of the chip or shaving upon the cutting edge of the tool. In carrying out this work Dr. Nicolson has designed and constructed what appears to be by far the most scientific apparatus which has yet been made for this purpose. In his paper (published in Transactions, Vol. 25), he has very fully illustrated the apparatus with which he weighs separately the pressure of the chip upon the tool in three directions:

a the VERTICAL PRESSURE;

b the outward pressure or the pressure horizontally at right angles to the axis of the piece being turned; called by him SURFACING PRESSURE;

c the feeding pressure or the pressure horizontally parallel to the axis of the piece being turned; called by him TRAVERSING PRESSURE.

88 His determination of that lip angle of the tool which cuts the metal with the least pressure was of great interest; but, in the writer's judgment, by far the most important and original fact developed by him was brought out by a series of experiments in which he determined the wave-like increase and decrease of the pressure upon the nose of the tool which occurs in cutting metals.

89 In these experiments the chip was removed at a cutting speed of about one foot in five hours. It is notable that no other apparatus heretofore designed was sufficiently scientific and accurate to demonstrate this fact.

90 The writer has taken the liberty of reproducing on Folder 12, Figs. 82 and 86, Dr. Nicolson's diagram, showing this variation in pressure. His discovery is most important in explaining one of the causes for the chattering of tools, and becomes a thoroughly scientific aid in selecting the shape or contour of the cutting edge for standard tools to be used in "roughing work."

91 These experiments form a substantial and permanent addition to our knowledge of the art of cutting metals; and the writer regrets that Dr. Nicolson has not since then investigated other elements immediately affecting the more vital problem of the cutting speed in a similarly thorough manner; since he chose for investigation that element which on the whole is least fruitful in its practical results upon the art of cutting metals, namely, the pressure of the chip upon the tool.

92 However, in choosing this element for investigation Dr. Nicolson made the same error (if such it may be called) into which almost every experimenter in this field fal s sooner or later. From all theoretical standpoints it appears to the novice that a thorough investigation of the effect of the pressure of the chip upon the tool under varying conditions must furnish the key to the whole problem of the variation of cutting speed due to varying feeds, depths of cut, shape of the tool, etc. The fact is, however, that every one who exploits this field finds out sooner or later that there is no traceable relation whatever between the pressure of the chip on the tool and the cutting speed, and but little connection even between the hardness of the metal and the pressure upon the tool. The following is the reasoning which has led us all, at one time or another, into the same error:

93 The ultimate cause for a tool giving out when cutting metal is the dullness or wear of the tool produced by the rubbing or pressure of the chip upon the lip surface of the tool, and the chief element causing this wear, particularly at the high speeds at which tools should be run to do their best work, is the softening of the tool due to the heat produced by the friction of the chip upon its lip surface. Now, it seems perfectly evident that this heat will be increased directly in proportion to three elements:

a the pounds of pressure of the chip upon the tool;

b the speed with which the chip slides across the nose of the tool;

c the coefficient of friction between the chip and the surface of the tool.

And yet, paradoxical as it may seem, the writer again repeats that there is no traceable relation between the pressure of the chip upon the tool and the cutting speed. (The reasons in detail for this will be found later in paragraphs 503 to 519.)

94 So convincing, however, is the above theory that each successive experimenter who has joined the writer in his work has been thoroughly convinced that, through some error in our early experiments upon the pressure of the chip on the tool, we failed to establish the relation between the pressure and the cutting speed which would be demonstrated by a more carefully tried set of experiments; and the writer thinks it is not an exaggeration to state that each of these men in succession remained unconvinced until he had had the opportunity of verifying this fact for himself.

95 As an illustration of the mental effect of this theory upon these experimenters: In one case, a bright and thoroughly honest young man, who was employed by the writer to help on the mathematical

side of this work, became so thoroughly convinced through the above reasoning that the main lines on which we were carrying on our investigation would be rendered entirely unnecessary by a series of pressure tests made by himself, that upon being told by the writer that he would not allow the expense to be incurred for another series of pressure tests, he wrote a memorial of many pages to the Board of Directors of the company in which the experiments were being carried on, explaining his own thorough scientific attainments and the writer's lack of the same, and that, therefore, our relative positions ought to be reversed, that he should do the directing and the writer shou'd do the work. And, finally, when his protests were not heeded, he resigned his position; and the writer has been told that he subsequently induced another company to allow him to experiment on his own account. However, up to date there has not appeared any published record of these experiments.

96 We are dwelling at such length upon this element in the art because it has constituted the pit into which so many experimenters have fallen; and upon failing to trace any scientific relation between the pressure and the cutting speed they are very apt to conclude that the whole subject of cutting metals belongs to the domain of "rule of thumb" rather than to that of exact science, and give up further work in this field.

97 It may almost be said that investigations heretofore made upon the general subject of the pressure of the chip upon the tool have proved barren of useful and practical results, except in so far as they have furnished the knowledge needed by tool builders for giving their machines the proper driving power. It is with little hesitation that the writer makes the assertion that if no experiments whatever had been made in this field, the knowledge of the art of cutting metals would be on the whole in a more advanced state than it is now, since experimenters in all countries instead of studying pressures would have given their attention to some one of the other lines of investigation which bear directly and yield valuable information upon the one most important subject of cutting speed.

98 It is a noteworthy fact that when thorough investigations are attempted by earnest men in new fields, while frequently the object aimed at is not attained, yet quite often discoveries are made which are entirely foreign to the purpose for which the investigation was undertaken. And it may be said that the indirect results of careful scientific work are, generally speaking, fully as valuable as the direct. Two interesting illustrations of this fact have been furnished by our experiments.

99 The discovery of the Taylor-White process of treating tools by heating them almost to the melting point, or, in other words, the intoduction of modern high speed tools the world over, was the indirect result of one of our lines of investigation.

100 The demonstration of the fact that the rules for using belting in common practice furnished belts which were entirely too light for economy was also one of the indirect results of our experiments.

101 The manner of making these discoveries was each time in a way so typical of what may be expected in similar cases that it would seem worth while to describe it in some detail.

102 During the winter of 1894–1895, the writer conducted an investigation in the shop of Wm. Sellers & Co., at the joint expense of Messrs. William Cramp & Sons, shipbuilders, and Messrs. Wm. Sellers & Co., to determine which make of self-hardening tool steel was, on the whole, the best to adopt as standard for all of the roughing tools of these two shops.

103 As a result of this work, the choice was narrowed down at that time to two makes of tool steel: (1) the celebrated Mushet self-hardening steel, the chemical composition of the particular bar analyzed at this time being as follows:

TUNGSTEN PER CENT	CHROMIUM PER CENT	CARBON PER CENT	MANGANESE PER CENT	SILICON PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT
5.441	0.398	2.150	1.578	1.044		

and (2) a self-hardening steel made by the Midvale Steel Company of the following chemical composition:

TUNGSTEN PER CENT	CHROMIUM PER CENT	CARBON PER CENT	MANGANESE PER CENT	SILICON PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT
7.723	1.830	1.143	0.180	0.246	0.023	0.008

104 Of these two steels, the tools made from the Midvale steel were shown to be capable of running at rather higher cutting speeds. The writer himself heated hundreds of tools of these makes in the course of his experiments in order to accurately determine the best temperatures for forging and heating them prior to grinding so as to get the best cutting speeds. In these experiments he found that the Mushet

steel if overheated crumbled badly when struck even a light blow on the anvil, while the Midvale steel if overheated showed no tendency to crumble, but, on the other hand, was apparently permanently injured. In fact, heating these tools slightly beyond a bright cherry red caused them to permanently fall down in their cutting speeds; and the writer was unable at that time to find any subsequent heat treatment which would restore a tool broken down in this way to its original good condition. This defect in the Midvale tools left us in doubt as to whether the Mushet or the Midvale was, on the whole, the better to adopt as a shop standard.

105 In the summer of 1898, soon after undertaking the reorganization of the management of the Bethlehem Steel Company, the writer decided to continue the experiments just referred to with a view to ascertaining whether in the meanwhile some better tool steel had not been developed. After testing several additional makes of tools, our experiments indicated that the Midvale self-hardening tools could be run if properly heated at slightly higher speeds than those of any other make.

106 Upon deciding to adopt this steel as our standard the writer had a number of tools of each make of steel carefully dressed and ground to exactly the same shape. He then called the foremen and superintendents of the machine shops of the Bethlehem Steel Company to the experimental lathe so that they could be convinced by seeing an actual trial of all of the tools that the Midvale steel was, on the whole, the best. In this test, however, the Midvale tools proved to be worse than those of any other make; *i. e.*, they ran at slower cutting speeds. This result was rather humiliating to us as experimenters who had spent several weeks in the investigation.

107 It was of course the first impression of the writer that these tools had been overheated in the smith shop. Upon careful inquiry among the smiths, however, it seemed as though they had taken special pains to dress them at a low heat, although the matter was left in much doubt. The writer, therefore, determined to make a thorough investigation before finally adopting the Midvale steel as our shop standard to discover if possible some heat treatment which would restore Midvale tools injured in their heating (whether they had been underheated or overheated) to their original good condition.

108 For this purpose Mr. White and the writer started a carefully laid out series of experiments, in which tools were to be heated at temperatures increasing, say, by about 50 degrees all the way from a black heat to the melting point. These tools were then to be ground

and run in the experimental lathe upon a uniform forging, so as to find:

a that heat at which the highest cutting speed could be attained (which our previous experiments had shown to be a cherry red);

b to accurately determine the exact danger point at which if over or underheated these tools were seriously injured;

c to find some heat treatment by which injured tools could be restored to their former high cutting speeds.

109 These experiments corroborated our Cramp-Sellers experiments, showing that the tools were seriously broken down or injured by overheating, say, somewhere between 1550 degrees F. and 1700 degrees F.; but to our great surprise, tools heated up to or above the high heat of 1725 degrees F. proved better than any of those heated to the best previous temperature, namely, a bright cherry red; and from 1725° F. up to the incipient point of fusion of the tools, the higher they were heated, the higher the cutting speeds at which they would run.

110 Thus, the discovery that phenomenal results could be obtained by heating tools close to the melting point, which was so completely revolutionary and directly the opposite of all previous heat treatment of tools, was the indirect result of an accurate scientific effort to investigate as to which brand of tool steel was, on the whole, the best to adopt as a shop standard; neither Mr. White nor the writer having the slightest idea that overheating beyond the bright cherry red would do anything except injure the tool more and more the higher it was heated.

111 During our early Midvale Steel Company experiments, extending from 1880 to 1883, the writer had so much trouble in maintaining the tension of the belt used in driving the boring mill upon which he was experimenting that he concluded: (1) that belting rules in common use furnished belts entirely too light for economy; and (2) that the proper way to take care of belting was to have each belt in a shop tightened at regular intervals with belt clamps especially fitted with spring balances, with which the tension of the belt was accurately weighed every time it was tightened, each belt being retightened each time to exactly the same tension.

112 In 1884, the writer designed and superintended the erection of a new machine shop for the Midvale Steel Company, and this gave him the opportunity to put these conclusions to a practical test. About half the belts in the shop were designed according to the ordinary rules and the other half were made about three times as

heavy as the usual standard. This shop ran day and night. The belts were in all cases cared for and retightened only upon written orders sent from the shop office; and an accurate record was kept through nine years of all items of interest concerning each belt, namely: the number of hours lost through interruption to manufacture; the number of times each belt interrupted manufacture; the orginal cost of each belt; the detail costs of tightening, cleaning and repairing each belt; the fall in the tension before requiring retightening; and the time each belt would run without being retightened. Thus at the end of nine years these belts furnished a record which demonstrated beyond question many important facts connected with the use of belting, the principal of these being that the ordinary rules gave belts only about one-half as heavy as should be used for economy.[1] This belting experiment illustrates again the good that often comes indirectly from experiments undertaken in an entirely different field.

113 After many years of close personal contact with our mechanics, I have great confidence in their good judgment and common sense in the long run, and I am proud to number many of them among my most intimate friends.

114 As a class, however, they are extremely conservative, and if left to themselves their progress from the older toward better methods will be exceedingly slow. And my experience is that rapid improvement can only be brought about through constant and heavy pressure from those who are over them.

115 It must be said, therefore, that to get any great benefit from the laws derived from these experiments, our slide rules must be used, and these slide rules will be of but little, if any, value under the old style of management, in which the machinist is left with the final decision as to what shape of tool, depth of cut, speed, and feed, he will use.

116 The slide rules cannot be left at the lathe to be banged about by the machinist. They must be used by a man with reasonably clean hands, and at a table or desk, and this man must write his instructions as to speed, feed, depth of cut, etc., and send them to the machinist well in advance of the time that the work is to be done. Even if these

[1] The writer presented a paper to this Society in 1893 (published in Transactions, Vol. 15) upon this series of experiments. He has since found, however, that in the minds of many readers the value of the conclusions arrived at have been seriously brought into question largely through the criticism of one man, which at the time appeared to the writer so ridiculous that he made the mistake of thinking it not worth answering in detail. This should be a warning to writers to answer carefully all criticisms, however foolish.

written nstructions are sent to the machinist, however, little attention will be paid to them unless rigid standards have been not only adopted, but ENFORCED, throughout the shop for every detail, large and small, of the shop equipment, as well as for all shop methods. And, further, but little can be accomplished with these laws unless the old style foreman and shop superintendent have been done away with, and functional foremanship has been substituted,—consisting of speed bosses, gang bosses, order-of-work men, inspector, time study men, etc. In fact, the correct use of slide rules involves the substitution of our whole task system of management for the old style management, as described in our paper on "Shop Management" (Transactions, Vol. 24). This involves such radical, one might almost say, revolutionary, changes in the mental attitude and habits both of the workmen and of the management, and the danger from strikes is so great and the chances for failure are so many, that such a reorganization should only be undertaken under the direct control (not advice but CONTROL) of men who have had years of experience and training in introducing this system.

117 A long time will be required in any shop to bring about this radically new order of things; but in the end the gain is so great that I say without hesitation that there is hardly a machine shop in the country whose output cannot be doubled through the use of these methods. And this applies not only to large shops, but also to comparatively small establishments. In a company whose employees all told, including officers and salesmen, number about one hundred and fifty men, we have succeeded in more than doubling the output of the shop, and in converting an annual loss of 20 per cent upon the old volume of business into an annual profit of more than 20 per cent upon the new volume of business, and at the same time rendering a lot of disorganized and dissatisfied workmen contented and hard working, by insuring them an average increase of about 35 per cent in their wages. And I take this opportunity of again saying that those companies are indeed fortunate who can secure the services of men to direct the introduction of this type of management who have had sufficient training and experience to insure success.[1]

118 Unfortunately those fundamental ideas upon which the new task management rests mainly for success are directly antagonistic to the fundamental ideas of the old type of management. To give two out of many examples: Under our system the workman is told

[1]The writer feels free to give this advice most emphatically without danger of having his motives misinterpreted, since he has himself given up accepting professional engagements in this field.

minutely just what he is to do and how he is to do it; and any improvement which he makes upon the orders given him is fatal to success. While, with the old style, the workman is expected to constantly improve upon his orders and former methods. Under our system, any improvement, large or small, once decided upon goes into immediate use, and is never a lowed to lapse or become obsolete, while under the old system, the innovation unless it meets with the approval of the mechanic (which it never does at the start) is generally for a long time, at least, a positive impediment to success. Thus, many of those elements which are mainly responsible for the success of our system are failures and a positive clog when grafted on to the old system.

119 For this reason the really great gain which will ultimately come from the use of these slide rules will be slow in arriving—mainly, as explained, because of the revolutionary changes needed for their successful use—but it is sure to come in the end.

120 Too much emphasis cannot be laid upon the fact that standardization really means simplification. It is far simpler to have in a standardized shop two makes of tool steel than to have 20 makes of tool steel, as will be found in shops under the old style of management. It is far simpler to have all of the tools in a standardized shop ground by one man to a few simple but rigidly maintained shapes than to have, as is usual in the old style shop, each machinist spend a portion of each day at the grindstone, grinding his tools with radically wrong curves and cutting angles, merely because bad shapes are easier to grind than good. Hundreds of similar illustrations could be given showing the true simplicity (not complication) which accompanies the new type of management.

121 There is, however, one element in which the new type of management to all outward appearance is far more complicated than the old; namely, no standards and no real system of management can be maintained without the supervision and, what is more, the hard work of men who would be called by the old style of management supernumeraries or non-producers. The man who judges of the complication of his organization only by looking over the names of those on the pay-roll and separating the so-called non-producers from the producers, finds the new style of management more complicated than the old.

122 No one doubts for one minute that it is far simpler to run a shop with a boiler, steam engine, shafting, pulleys and belts than it would be to run the same shop with the old fashioned foot power, yet the boiler, steam engine, shafting, pulleys and belts require, as supernumeraries or non-producers on the pay-roll, a fireman, an engineer,

an oiler and often a man to look after belts. The old style manager, however, who judges of complication only by comparing the number of non-producers with that of the producers, would find the steam engine merely a complication in management. The same man, to be logical, would find the whole drafting force of an engineering establishment merely a complication, whereas in fact it is a great simplification over the old method.

123 Now our whole system of management is quite accurately typified by the substitution of an elaborate engine to drive and control the shop in place of the old fashioned foot power. There is no question that our human managing machine, which is required for the maintenance and the effective use of both standard shop details, and standard methods throughout the establishment, calls for many more non-producers than are used with the old style management having its two or three foremen and a superintendent. The efficiency of our engine of management, however, compared with the old single foreman is like a shop engine as compared with foot power or the drafting room as compared with having the designing done by the pattern maker, blacksmith and machinist.

124 A study of the recommendations made throughout this paper will illustrate the fact that we propose to take all of the important decisions and planning which vitally affect the output of the shop out of the hands of the workmen, and centralize them in a few men, each of whom is especially trained in the art of making those decisions and in seeing that they are carried out, each man having his own particular function in which he is supreme, and not interfering with the functions of other men. In all this let me say again that we are aiming at true simplicity, not complication.

125 There is one recommendation, however, in modern machine shop practice in making which the writer will probably be accused of being old fashioned or ultra-conservative.

126 Of late years there has been what may be almost termed a blind rush on the part of those who have wished to increase the efficiency of their shops toward driving each individual machine with an independent motor. The writer is firmly convinced through large personal observation in many shops and through having himself systematized two electrical works that in perhaps three cases out of four a properly designed belt drive is preferable to the individual motor drive for machine tools. There is no question that through a term of years the total cost, on the one hand, of individual motors and electrical wiring, coupled with the maintenanace and repairs, of this system will far exceed the first cost of properly designed shafting

and belting plus maintenance and repairs (in most shops entirely too light belts and counter shafts of inferior design are used, and the belts are not systematically cared for by one trained man and this involves a heavy cost for maintenance). There is no question, therefore, that in many cases the motor drive means in the end additional complication and expense rather than simplicity and economy.

127 It is at last admitted that there is little, if any, economy in power obtainable through promiscuous motor driving; and it will certainly be found to be a safe rule not to adopt an individual motor for driving any machine tool unless clearly evident and a large saving can be made by it.

128 In concluding let me say that we are now but on the threshold of the coming era of true coöperation. The time is fast going by for the great personal or individual achievement of any one man standing alone and without the help of those around him. And the time is coming when all great things will be done by the coöperation of many men in which each man performs that function for which he is best suited, each man preserves his own individuality and is supreme in his particular function, and each man at the same time loses none of his originality and proper personal initiative, and yet is controlled by and must work harmoniously with many other men.

129 And let me point out that the most important lessons taught by these experiments, particularly to the younger men, are:

SEVERAL MEN WHEN HEARTILY COÖPERATING, EVEN IF OF EVERYDAY CALIBER, CAN ACCOMPLISH WHAT WOULD BE NEXT TO IMPOSSIBLE FOR ANY ONE MAN EVEN OF EXCEPTIONAL ABILITY.

EXPENSIVE EXPERIMENTS CAN BE SUCCESSFULLY CARRIED ON BY MEN WITHOUT MONEY, AND THE MOST DIFFICULT MATHEMATICAL PROBLEMS CAN BE SOLVED BY VERY ORDINARY MATHEMATICIANS; PROVIDING ONLY THAT THEY ARE WILLING TO PAY THE PRICE IN TIME, PATIENCE AND HARD WORK.

THE OLD ADAGE IS AGAIN MADE GOOD THAT ALL THINGS COME TO HIM WHO WAITS, IF ONLY HE WORKS HARD ENOUGH IN THE MEANTIME.

DEFINITIONS

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	TEXT PARAGRAPHS	FOLDERS
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For data concerning additional experiments and investigations, see paragraph 1198

ON THE ART OF CUTTING METALS

PART 2*

Division—Details of Experiments—Laws Deduced—Practical Application of Laws

130 There are three principal objects in writing this section of the paper.

131 (A) To record and make public the results of our experiments to date as embodied in laws, etc., and the incorporation of these laws in slide rules for practical, everyday use.

132 (B) To describe the methods, principles and apparatus which should be used in making investigations of this type, and warn future experimenters against the errors into which we, as well as most other investigators in this field, have fallen.

133 (C) To indicate the additional experiments which are needed to perfect our knowledge of the art, in the hope of inducing others to join us in carrying on and completing this work, both in the interest of science and of the many users of machine tools the world over; and to warn others against a certain class of experiments which are alluring, appear to offer great opportunities, but which, in fact, are fruitless.

134 The writer wishes to emphasize the fact that, while many of our experiments have a certain scientific value, and while it has been our effort to conduct all of our work upon scientific principles, yet the main object of this investigation has been the thoroughly practical one of enabling us to get more, better and cheaper work out of a machine shop.

135 The problem before us may be again briefly stated to consist of a careful study of the effect which each of the twelve following variable elements has upon the selection of the CUTTING SPEED OF THE TOOL:

* The subjects treated in this section of the paper are from their nature so dependent one upon another, and so interwoven, that the writer has had difficulty in treating them consecutively and logically. He therefore trusts that a certain amount of repetition and the necessity for referring frequently from one part of the paper to another will be pardoned.

a the quality of the metal which is to be cut, *i. e.*, its hardness or other qualities which affect the cutting speed;

b the diameter of the work;

c the depth of the cut, or one-half of the amount by which the forging or casting is being reduced in diameter in turning;

d the thickness of the shaving, or the thickness of the spiral strip or band of metal which is to be removed by the tool, measured while the metal retains its original density; not the thickness of the actual shaving, the metal of which has become partly disintegrated;

e the elasticity of the work and of the tool;

f the shape or contour of the cutting edge of the tool, together with its clearance and lip angles;

g the chemical composition of the steel from which the tool is made, and the heat treatment of the tool;

h whether a heavy stream of water, or other cooling medium, is used on the tool;

j the duration of the cut, *i. e.*, the time which a tool must last under pressure of the shaving without being reground;

k the pressure of the chip or shaving upon the tool;

l the changes of speed and feed possible in the lathe;

m the pulling and feeding power of the lathe at its various speeds.

136 It is of course superfluous to call the attention of those who have given much thought to the subject of cutting metals as an art, to the fact that the ultimate object of all experiments in this field is to learn how to remove the metal from our forgings and castings in the quickest time, and that therefore the art of cutting metals may be briefly defined as the knowledge of how, with the limitations caused by some and the opportunities offered by others of the above twelve variable elements, in each case to remove the metal with the highest appropriate cutting speed. And yet a walk through almost any machine shop will convince anyone that if those in charge of the shop are aware of the effect of speed upon economy, they are acting upon this information only in a few sporadic cases and by no means systematically.

137 Before entering upon the details of our experiments, it seems necessary to again particularly call attention to the fact that "standard cutting-speed" is the true criterion by which to measure the

effect of each of these twelve variables upon the problem. The writer therefore repeats what he has before said in paragraph 64 (Part 1):

"THE EFFECT OF EACH VARIABLE UPON THE PROBLEM IS BEST DETERMINED BY FINDING THE EXACT RATE OF CUTTING SPEED (SAY, IN FEET PER MINUTE) WHICH WILL CAUSE THE TOOL TO BE COMPLETLY RUINED AFTER HAVING BEEN RUN FOR 20 MINUTES UNDER UNIFORM CONDITIONS."

138 To give another illustration of our practical use of this standard. If, for example, we wish to determine which make of tool steel is the best, we should proceed to make from each of the two kinds to be tested a set of from four to eight tools. Each tool should be forged from tool steel, say, $\frac{1}{8}$ inch x $1\frac{3}{8}$ inch and about 18 inches long, to exactly the same shape, and after giving the tools made from each type of steel the heat treatment appropriate to its chemical composition, they should all be ground with exactly the same shaped cutting edge and the same clearance and lip angles. One of the sets of eight tools should then be run, one tool after another, each for a period of 20 minutes, and each at a little faster cutting speed than its predecessor, until that cutting speed has been found which will cause the tool to be completely ruined at the end of 20 minutes, with an allowance of a minute or two each side of the 20-minute mark.

139 Every precaution must be taken throughout these tests to maintain uniform all of the other elements or variables which affect the cutting speed, such as the depth of the cut and the quality of the metal being cut. The rate of the cutting speed must be frequently tested during each 20-minute run to be sure that it is uniform throughout. For further details in making tests, see paragraphs 175 to 262.

140 Throughout this paper, "the speed at which tools" give out in 20 minutes, as described above, will be, for the sake of brevity, referred to as the "standard speed."

141 After having found the "standard speed" of the first type of tools, and having verified it by ruining several more of the eight tools at the same speed, we should next determine in a similar manner the exact speed at which the other make of tools will be ruined in 20 minutes; and if, for instance, one of these sets of tools exactly ruins at a cutting speed of 55 feet, while the other make ruins at 50 feet per minute, these "standard speeds," 55 to 50, constitute by far the most important criterion from which to judge the relative economic value of the two steels for a machine shop.

142 Other properties of the steels, as mentioned in paragraphs 934 to 1094, must of course be considered in choosing a tool steel. But if

the steels are in other respects equal, their maximum cutting speeds then represent the exact measure of their values.

143 Perhaps the best criterion by which to judge of the value of any standard or test is the ability to duplicate the results which have been once obtained. We have repeatedly been able to reduplicate the results obtained through this standard within an error of 2 per cent.

"STANDARD SPEED" BEST TEST FOR DETERMINING VALUE OF TOOLS, ETC.

144 It seems necessary early in this paper to emphasize the importance of the "standard speed" as being the true test for the relative value of tools as well as for the other elements involved in the art of cutting metals—the more so since the accuracy and delicacy of this standard are but vaguely recognized.

145 Among those commonly referred to, the most deceptive and unreliable standard as to the relative value of tools is THE LENGTH OF TIME A TOOL WILL RUN BEFORE REQUIRING GRINDING or before being ruined. So many people are continually being misled by this standard that its inadequacy can scarcely be over-emphasized.

146 To illustrate: Let us assume, for instance, that three tools have been proved to be uniform within, say, 2 per cent by our standard method, described in paragraph 138, and to have a "standard speed" of 60 feet per minute for a run of 20 minutes. If then the cutting speed of each of these tools is increased, say, to 63 feet per minute, THE LENGTH OF TIME WHICH THEY WILL RUN at this slight increase in cutting speed will be almost sure to vary greatly. One of the tools will be ruined, say, in six minutes, another in nine minutes, while the third may last 15 minutes. Thus if tools which are uniform within 2 per cent are run only slightly beyond "standard speed," they are likely to vary to the extent of more than 2 to 1 in time which they last before ruining or requiring regrinding; and so the misleading nature of the standard becomes apparent.

147 The great variation in the time which carefully standardized tools will last when run at an increase in cutting speed of only one foot per minute will be seen by examining table in paragraph 619. In this case it will be seen that an increase of only one foot in cutting speed causes standardized tools to vary in their running period, in the two extreme cases, between the periods of $1\frac{1}{2}$ minutes and $17\frac{1}{2}$ minutes. A study of this table will show that the value of the tools is closely given by standard cutting speeds, but that it is in no sense proportional to the time which the tool runs before

being ruined. This matter will be further discussed in paragraph 619.

148 The inadequacy of this standard is, however, so little recognized that even as able an experimenter as Dr. Nicolson, after having written the record of the "Manchester Experiments," and then made his own admirable "Dynamometer Experiments," falls into the error of adopting this false standard in his "Experiments on Durability of Different Cutting Angles," described in his paper in Tables 5, 6 and 7, and in paragraphs 38 to 44 inclusive, pp. 657 to 661. Yet in these very experiments the misleading nature of this standard will be seen. Note that in Table 7, for instance, a 75 degree angle tool at a cutting speed of 74 feet per minute lasts only 2 minutes 10 seconds, while the same tool when run only one foot per minute slower at a cutting speed of 73 feet per minute lasts 10 minutes and 37 seconds.

149 For many years it has been usual for salesmen of tool steels to give detailed accounts of the number of hours which tools made from their steels, would cut metals without the necessity of regrinding. In fact, tool steel literature abounds in statements of the long life of tools with one grinding, implying that this is the proper standard for measuring their value. By referring, however, to paragraphs 693 and 710 it will be seen that for ninety-nine one-hundredths of the work of a shop, this criterion is of no value whatever, and that the man who boasts of having run a tool without regrinding, say, for a longer period than one and one-half hours on ordinary shop work, is merely boasting of how little he knows about the art of cutting metals cheaply.

150 The writer has already referred in paragraph 92 (Part 1) to another error into which all experimenters in this art fall sooner or later: namely, that of concluding that the effect which the size, shape and angles of the tool has upon the problem of cutting metals can best be determined by a careful investigation of the effect which each of these elements has upon the pressure required to remove a given sized chip or shaving. The reasoning used is that that tool is the best which is so shaped as to remove a given chip or shaving with the least amount of pressure or cutting force. The utter fallacy of this as a measure of the value of the tool has already been referred to in paragraph 92, and will be again referred to in paragraph 135.

151 In paragraph 59 (Part 1) the writer has described several false standards which were adopted by us, one after another, for determining when a tool had been run at its maximum cutting

speed. Even with these defective standards we obtained most useful results. Broadly speaking, however, our reason for successively abandoning each of these standards was the impossibility of accurately reduplicating the results obtained. And this after all remains the best gage of the value of experimental methods. In all cases the earlier standards adopted by us required very close observation and judgment on the part of the experimenter to determine when the tool had reached that state of deterioration which was appropriate to its highest cutting speed. The advantage of our present standard, namely, that of completely ruining the tool, lies in the fact that it is an unmistakable, clear-cut phenomenon which calls for a minimum of judgment on the part of the operator, and thus eliminates one of the sources of human error in the experiments, and enables us to reduplicate our results with accuracy.

152 On Folder 3, Fig. 17b, are shown several views of a tool which has been completely ruined according to this standard.

ACTION OF TOOL AND ITS WEAR IN CUTTING METALS

THE ACTION OF THE NOSE OF THE TOOL

153 On Folder 8, Figs. 42, 43 and 44, is illustrated in enlarged views the action of a tool in cutting a chip or shaving from a forging at its proper normal cutting speed. It may be said in the case of all "roughing cuts" that the chip is torn away from the forging rather than removed by the action which we term cutting. The familiar action of cutting, as exemplified by an axe or knife removing a chip from a piece of wood, for instance, consists in forcing a sharp wedge (*i. e.*, one whose two flanks form an acute angle) into the substance to be cut. Both flanks of the wedge press constantly upon the wood, one flank bearing against the main body of the piece, while the other forces or wedges the chip or shaving away.

154 While a metal cutting tool looks like a wedge, its cutting edge being formed by the intersection of the "lip surface" and "clearance surface" or flank of the tool, its action is far different from that of the wedge. Only one surface of a metal cutting tool, the lip surface, ever presses against the metal. The clearance surface, as its name implies, is never allowed to touch the forging. Thus "cutting" with a metal cutting tool consists in pressing, tearing or shearing the metal away with the lip surface of the "wedge" only under pressure, while in the case of the axe and other kinds of cutting, both wedge surfaces are constantly under pressure.

155 After the cut has once been started, and the full thickness of the shaving is being removed, the action of the tool may be described as that of tearing the chip away from the body of the forging and then shearing it up into separate sections; the portion of the chip which has just been torn away, and which is still pressing upon the lip surface of the tool, acting as a lever by which the following portion of the chip is torn away from the main body of the metal.

156 It may be of interest to analyze to a certain extent the nature of the forces to which a chip and the forging from which it is being removed are subjected through the tearing action of the tool. The enlarged view of the chip, tool and forging, shown in Folder 8, Fig. 42, represents with fair accuracy the relative proportions which the shaving cut from a forging of mild steel (say, 60,000 lbs. tensile strength and 33% stretch) finally assumes with relation to the original thickness of the layer of metal which the tool is about to remove. It is, of course, impossible to accurately determine the extent to which various parts of the chip and forging close to the tool are under compression and tension, but in general the theory advanced is believed to be correct.

157 Referring to Folder 8, Fig. 42, the forging being cut and the nose of the tool which is removing the chip are shown on an enlarged scale. The thickness of the layer of metal about to be removed is indicated by L between the dotted line and the full line which represents the outside of the forging. It will be observed that the chip is in process of being torn apart and broken up into three sections: Section 1, which is adjoining the forging; section 2, which comes next to it, and in which rupture or cleavage has started and proceeded a a little way up from the bottom of the chip and on the left hand side, the shearing action having progressed as far as T_2; section 3, in which shearing has progressed about two-thirds of the way to the top of the chip and is taking place at T_3. Section 4 has been entirely sheared from its adjoining section, and has already left the lip surface of the tool.

158 On examination of the proportions of the chip it will be noticed that the width of the sections into which the chip breaks up is at their base about double the thickness of the original layer of metal which is to be removed, and that their upper portions are not enlarged to the same extent. These sections are about three times as high as the original thickness of the layer of the metal to be removed. It should be clearly understood that the dimensions of the section of the chip will vary with each hardness of metal which is being cut, and also to a certain extent with the sides and back slopes of the lip

surface of the tool. The harder the metal of the forging, the less will each section into which the chip has been broken up be found to be enlarged. In other words, if the same shaped tool be used in each case the chip from soft metal enlarges or distorts very much more than the corresponding chip from hard steel. This will be referred to in paragraph 506, in explaining the reason why the total pressure on the tool has but little relation on the one hand to the cutting speed, and on the other hand to the hardness of the metal which is being cut.

159 The chip bears on the surface of the forging, say, from point H to point G, and throughout this distance is under constant compression from the lip surface of the tool. This compression is transmitted through each of the sections 1 and 2 of the chip, in the direction indicated by the small arrows, to the upper portions of these sections, which are still unbroken and act like a lever attached to the upper part of section 1 to tear section 1 away from the body of the forging, as indicated at point T_1. The tearing away of section 1 is also assisted by the pressure of the tool upon its lower surface.

160 After this tearing action has started, the further breaking of the chip into independent sections would seem to be that of simple shearing. It should be borne in mind that in shearing a thick piece of steel the whole piece is not shorn or cut apart at the same instant, but the line at which rupture or cleavage takes place progresses from one surface of the piece down through the metal until within a short distance from the other surface, when the whole remaining section rather suddenly gives way.

161 In shearing steel, the metal at the point of rupture is pulled apart under a tensile strain, although on each side of the shearing line the metal is under heavy compression.

162 As each of the sections of the chip successively comes in contact with the lip of the tool, its lower surface is crushed, and the metal flows and spreads out laterally until it becomes about twice its original thickness. As in all shearing, when the full capacity for flowing of the metal has been reached, it tears apart under tensile strain from the body of the adjoining metal of the forging. The compression on the chip from the tool still continues, however, and the chips continue to flow and spread out sideways at a part higher up; *i. e.*, farther away from the surface of the tool, at the portions marked F. In the same way shearing continually takes place at the left side of the portion of the chip which is flowing or spreading out sideways.

163 There is no question that shearing takes place constantly along the left hand edges of two of the sections of the chip at the same

time, and it is probable that this action occurs most of the time along three lines of cleavage. See paragraph 167.

164 Dr. Nicolson's dynamometer experiments show that the pressure of the chip on the tool in cutting a chip of uniform section varies with wavelike regularity, and that the smallest pressure of the chip is not less than two-thirds of the greatest pressure. From this it is evident that shearing must be taking place along at least two lines of cleavage at the same time; since if each of the sections into which the chip is divided were completely broken off before the tool began to break off the following section, it is evident that there would be times when there was almost no pressure from the chip on the tool.

165 It is at first difficult to see how it is possible for the chip to be shearing at two or three places at the same time. It should be noted, however, that above the points T_1, T_2, T_3, the metal of the chip is still a solid part of the forging, and moves down at the same speed as the forging in a single mass, or body, toward the lip surface of the tool; and with sufficient force to cause each of the three sections of the chip to flow or spread out at the parts indicated by the three letters *F*. According to the laws which govern shearing, rupture or cleavage in each case must take place as soon as the maximum possibility for flowing has been reached, and in each case shearing must occur at the left of the zone where the metal is flowing.

166 It is probable that after the shearing action has progressed in section 3 to about the point indicated by T_3, that the whole of this section gives way or shears with a rather sudden yielding of the metal from T_3, to the upper surface of the chip. It is this rather sudden shearing point which undoubtedly causes the wavelike diminution in the pressure of the chip indicated in Dr. Nicolson's experiments, referred to in paragraph 316.

167 By suddenly stopping one of our standard tools when cutting at full speed, we have clearly seen this shearing action taking place at two sections of the chip at the same time, and rupture had not completely taken place at the extreme upper part of the third section. In making an observation of this kind great care must be taken before stopping the lathe to be sure that in the tool to be observed there is not the slightest tendency to chatter, and the lathe driving parts should be massive in proportion to the sized cut being taken, as otherwise the elasticity left in the driving shafts causes an abnormal action of the tool at the instant the work stops, and produces a chip, of thicker section than the normal, which is completely severed from the body of the metal.

168 While the proportions of the chip and the section into which

it is broken are fairly true representations of fact, yet it must be borne in mind that the lines illustrating the strains to which the chips are submitted, as well as the progress made in the shearing of the chip, are merely submitted as illustrating a theory advanced by us to explain the facts. We are, however, more or less suspicious of all theories, our own as well as those of others.

169 Throughout this paper the important facts stated by us have been verified by many and carefully made experiments; and we therefore trust that our readers, if unable to accept our theories, will at least have respect for our facts.

ACTION OF CUTTING EDGE OF TOOL IS THAT OF SCRAPING—CUTTING EDGE NOT UNDER HEAVY PRESSURE

170 It would appear that the chip is torn off from the forging at a point appreciably above the cutting edge of the tool and this tearing action leaves the forging in all cases more or less jagged or irregular at the exact spot where the chip is pulled away from the forging, as shown to the left of T_1. An instant later the line of the cutting edge, or more correctly speaking, the portion of the lip surface immediately adjoining the cutting edge, comes in contact with these slight irregularities left on the forging owing to the tearing action, and shears these lumps off, so as to leave the receding flank of the forging comparatively smooth.

171 Thus in this tearing action, particularly in the case of cutting a thick shaving, while the cutting edge of the tool is continually in action, scraping or shearing off or rubbing away these small irregularities left on the forging, yet that portion of the lip surface close to the cutting edge constantly receives much less pressure from the chip than the same surface receives at a slight distance away from the cutting edge. This allows the tool to run at higher cutting speeds than would be possible if the cutting edge received the same pressure as does the lip surface close to it.

172 There are many phenomena which indicate this tearing action of the tool. For example, it is an everyday occurrence to see cutting tools which have been running close to their maximum speeds and which have been under cut for a considerable length of time, guttered out at a little distance back of the cutting edge, as shown in Folder 3, Fig. 17e. The wear in this spot indicates that the pressure of the chip has been most severe at a little distance back from the edge.

173 Still another manner in which in many cases the tearing action of the tool is indicated is illustrated in Folder 3, Fig. 17a, in which a

small mass of metal *D* is shown to be stuck fast to the lip surface of the tool after it has completed its work and been removed from the lathe. When broken off, however, and carefully examined, this mass will be found to consist of a great number of small particles which have been cut or scraped off of the forging, as above described, by the cutting edge of the tool. They are then pressed down into a dense little pile of compacted particles of steel or dust stuck together and to the lip surface of the tool almost as if they had been welded. In the case of the modern high speed tools, when this little mass of dust or particles is removed from the upper surface of the tool, the cutting edge will in most cases be found to be about as sharp as ever, and the lip surface adjacent to it when closely examined will show in many cases the scratches left by the emery wheel from the original grinding of the tool.

174 With roughing tools made from old fashioned tempered steel, however, and which have been speeded close to their "standard speeds," in most cases after removing this "dust pile" from the lip surface, the cutting edge of the tool will be found to be distinctly rounded over. And in cases where the tool has been cutting a very thick shaving, the edge will be very greatly rounded over, as shown in the enlarged view of the nose of a tool in Folder 7, Fig. 41.

NATURE OF WEAR ON TOOLS DEPENDS UPON WHETHER IT HAS BEEN CHIEFLY CAUSED BY HEAT

175 The appearance of tools which are worn down so as to require regrinding differs widely according to whether or not the heat produced by the pressure of the chip has been the chief cause of wear; and according to the part which heat has played in producing the wear, worn out tools may properly be divided into three classes.

THE FIRST CLASS

176 Tools in which the heat, produced by the pressure of the chip, has been so slight as to have had no softening effect upon the surface of the tool.

THE THIRD CLASS

177 Tools in which the heat has been so great as to soften the lip surface of the tool beneath the chip almost at once after starting the cut, and in which, therefore, heat has played the principal part in the wear of the tool.

THE SECOND CLASS

178 Tools in which the heat only slightly softens the surface of the tool during the greater part of the time that it is cutting, while during the latter part of the time heat is the chief cause of wear because, as described in the third class, it greatly softens the lip surface under pressure of the chip.

179 In the FIRST CLASS, in which heat plays no part in the wear of tools, all tools (whether made from carbon tempered steel, or from the old style self-hardening steel, or from the modern treated tools) wear in about the same manner. Namely, the lip surface just back of the cutting edge is slowly rubbed or worn or ground down through the friction of the chip, as shown in Folder 3, Fig. 17d.

180 As the surface of the tool through the long rubbing of the chip becomes slightly roughened, the tool wears away somewhat more rapidly, but the increase in the rapidity of wear is in this case by no means marked.

181 On the other hand, tools which wear according to the THIRD CLASS begin to distinctly deteriorate within from one to three minutes after the chip has started to cut, depending upon the length of time required for the friction of the chip to raise the tool from its normal cold state to the high temperature which corresponds to the combination of pressure and speed which produces the heat. And the moment the nose of the tool has reached a degree of heat at which the metal under the chip becomes distinctly soft, the wear then proceeds with great rapidity. Sometimes after arriving at a certain degree of softness, the heat remains approximately constant, and the wear upon the tool continues at a uniformly rapid rate until a comparatively deep groove or gutter has been worn into the lip surface. At other times after the lip surface of the tool begins to soften, it appears to become rougher and cause a still greater amount of friction and heat, in which case the wear of the tool proceeds at an increasingly rapid rate, and the tool is soon destroyed. There are rare instances in which after the rapid wear has started, the friction between the chip and the tool, for some unaccountable reason, appears to become less and the tool slightly cools down. Cases have come under the observation of the writer in which tools which had been running with their noses at a visible dark red heat, cooled off to such an extent that the chip which had been very dark blue in color changed to a color but slightly darker than a brown. This indicated a very marked diminution in friction, although the cutting speed was maintained at a uniform rate throughout. This case, however, is of rare occurrence.

182 While a deep groove worn by the chip is a characteristic of wear of the third class, by no means all of the tools in this class wear into a deep groove. Most of them give out before the groove has had time to wear deep. After wear of the third class has started, tools will generally be completely ruined in a time varying from 20 seconds to 15 minutes, and the time which elapses between the softening of the lip surface and the final ruining of the tool is exceedingly irregular. One of two tools—which have been proved through standardization to be uniform within, say, 1 or 2 per cent, may give out within one minute after this action starts, while the other may last 15 minutes. On the other hand, occasional lots of tools are found which, after having been proved uniform through standardization, will last under this softening speed for approximately the same length of time.

REASON FOR ADOPTING A STANDARD TEST PERIOD OF 20 MINUTES

183 It is this irregularity in the ruining time of tools belonging to the third class which has led us to adopt a trial period of 20 minutes as being the SHORTEST RUINING TIME from which it is safe to draw any correct scientific conclusions from tests in the art of cutting metals.

184 A cutting speed which causes the tool to be ruined in a shorter period than 20 minutes is accompanied by such a high degree of heat as to produce irregularity in the ruining time; on the other hand, a speed which ruins at the end of 20 minutes is accompanied by that degree of heat at which tools, generally speaking, can be depended upon to wear uniformly. In other words, it represents the degree of heat at which a lot of uniform tools will all give out at about the same time.

ECONOMICAL CUTTING SPEEDS

185 Cutting speeds which are sufficiently slow to cause the tool to wear as described in the first class are entirely too slow for economy. On the other hand, tools when run at the high cutting speeds which produce wear of the third class last so short a time that these high speeds are entirely out of the question for daily shop use.

186 It is then with cutting speeds causing wear of the SECOND CLASS that we are chiefly concerned; as it is within this range of cutting speeds that almost all roughing tools in every day use should be run for maximum all-round economy. CUTTING SPEEDS OF THIS CLASS ARE REFERRED TO AS "ECONOMICAL SPEEDS" OR "MOST ECON-

OMICAL SPEEDS." Our experiments, therefore, have been practically confined to a study of cutting speeds of the second class.

187 By referring to paragraph 701, and Folder 15, Table 105, it will be noted that a cutting speed which will cause a given tool to be ruined at the end of 80 minutes is about 20 per cent slower than the cutting speed of the same tool if it were to last 20 minutes. By referring also to paragraph 717, it will be noted that, on the whole, we have concluded it is *not* economical to run roughing tools at a cutting speed so slow as to cause them to LAST FOR MORE THAN ONE AND ONE-HALF HOURS without being reground. Tools which are ruined in one and one-half hours, however, are still within the second class as far as the causes for wear are concerned; and the wear of tools of the second class may be again referred to as being during the greater part of the life of the tool similar to the wear of the first-class tools, in which the heat is not sufficiently great to materially soften the lip surface. In the second class, however, the cutting speeds are so high as to cause the lip surface of the tool to gradually become rougher and rougher, and as this surface roughens, the heat increases so that in their final wearing out, say, during the last five to fifteen minutes of their life, tools of the second class wear in a manner similar to those of the third class. Thus it is seen that wear in tools of the second class is a combination of the type of wear of the first class with the type of wear of the third class, the first class type of wear extending through the greater part of the time that the tool is cutting.

HOW CARBON STEEL TEMPERED TOOLS AND TOOLS MADE FROM OLD FASHIONED SELF-HARDENING STEEL WEAR

189 With carbon steel tempered tools at standard speeds the cutting edge begins to be injured almost as soon as the tool starts to work, and is entirely rounded over and worn away before the tool finally gives out, and the tool works well in spite of its cutting edge being damaged. While with high speed tools at standard speeds, the cutting edge remains in almost perfect condition until just before the tool gives out, when even a very slight damage at one spot on the cutting edge will usually cause the tool to be ruined in a few revolutions.

190 Carbon tempered tools and also, to a considerable extent, the old fashioned self-hardening tools (such as Mushet), when run at their "economical" or "standard" speeds, pass through the following characteristic phases as they progress toward the point at which they are finally ruined. It will of course be understood that the "round-

ing of the cutting edge," the "mounting of the steel upon the lip" and the "rubbing away beneath the cutting edge" all progress simultaneously, although each of these phenomena is separately described.

191 The line of the cutting edge of the tool, which is at first keen, becomes very slightly dull so that it shines when held in the light, and it is then gradually rounded over until it finally loses all resemblance to a cutting edge, and after severe use frequently looks as if it had been purposely rounded over. This action is referred to in recording our experiments as "CUTTING EDGE ROUNDED."

192 The lip, or top surface of the tool, soon becomes slightly roughened and whitened as the shaving presses against it, then the surface of the tool near the cutting edge becomes discolored as if the temper of the tool were being drawn, and this discoloration increases both in the extent of its area and in its approach toward almost a black color, until the tool is entirely ruined. This action is referred to as "DISCOLORED BACK FROM CUTTING EDGE."

193 The flank of the tool begins to discolor in a manner similar to the lip and this discoloration continues to increase until the tool is finally ruined. This action is referred to as "DISCOLORED BELOW CUTTING EDGE."

194 Long before the tool is ruined, also, the fine particles of steel or dust scraped off by the cutting edge begin to weld or stick to the lip of the tool and mount upon it sometimes from $\frac{1}{16}$ inch to $\frac{1}{4}$ inch in height, as shown in Folder 3, Fig. 17d; referred to as "STEEL MOUNTED ON LIP."

195 The flank of the tool just below the cutting edge begins to wear or rub away slightly, and this wear gradually extends further and further below the cutting edge until the tool is ruined; referred to as "RUBBED BENEATH CUTTING EDGE."

196 Small portions of the metal being cut wedge themselves in between the flank of the tool and the work, and are partly welded or stuck to the tool, and these lumps which are welded on to the tool, and the rubbing away of the flank as the tool grows dull, prevent the feed from being uniform in thickness, and cause the tool sometimes to entirely skip its feed for one or two revolutions; referred to as "TOOL JUMPED." These lumps also force the work and the tool away from one another, and so leave the work rough and lumpy in these places; referred to as "LEFT LUMPY FINISH." Also the particles of metal which are welded on to the flank of the tool frequently leave scratches on the finished part of the work; referred to as "LEFT SCRATCHY FINISH."

197 The tool is finally completely ruined by having so much of

its flank rubbed away beneath the cutting edge, that no amount of pressure can force it into the work, and when it reaches this condition it must be immediately removed from the tool post, or there is danger of breaking either the tool, the machine, or the work.

198 As a result of our experiments it became evident that in case of tools made from the "low speed" self-hardening steels, for instance, such as the old fashioned Mushet steel, the tools would in many cases run successfully long after the line of the cutting edge had become slightly injured; also that in the case of "roughing" tools made from the carbon or tempered steels, it was economical and right in daily shop practice to run these tools at such a cutting speed that their actual cutting edges rounded off quite soon after starting to do their work. These tools continued to cut with their edges rounded, somewhat as shown in Folder 7, Fig. 42, successfully through the whole cut.

199 As stated in paragraph 67, all of our experiments made with these two types of tools (carbon and Mushet types) to determine the laws for cutting metals were rendered much more difficult, owing to the judgment required in deciding the exact amount of damage which was appropriate both to the tool and the particular thickness of shaving which was being taken.

200 In paragraph 506 will be found a further discussion of the very great part which the heat caused by the friction of the chip against the lip surface of the tool plays in ruining tools, and in paragraph 965 we refer to the peculiar property of retaining their hardness even at a high heat as being the essential novelty in the discovery of new "high speed" tools.

201 As stated above, in the case of modern high speed tools, the damage caused to the tool through the action of cutting is confined almost entirely to the lip surface of the tool. Doubtless also the metal right at the cutting edge of the tool remains harder than it is directly under the center of pressure of the chip, because the cutting edge is next to and constantly rubs against the cold body of the forging, and is materially cooled by this contact.

202 Whether the lip surface be ground away at high speeds or at slower speeds, the nose of the tool is generally "ruined" in a very short time after the cutting edge has been so damaged that it fails to scrape off smoothly even at one small spot the rough projections which have been left on the body of the forging by tearing away the chip. The moment the body of the forging begins to rub against the clearance flank of one of these high speed tools at or just below the cutting edge, even at one small place, the friction at this point gener-

ates so high a heat as to soften the tool very rapidly. After a comparatively few revolutions, the cutting edge and flank of the tool beneath it will be completely rubbed and melted away, as shown in Folder 3, Fig. 17b.

203 The above characteristic of holding their cutting edges in practically perfect condition while running at economical speeds up to the ruining point is a valuable property of the high speed tools, since it insures a good finish, and the maintenance throughout the cut of the proper size of the work, without the constant watchfulness required on the part of the operator in the case of old slow speed tools with their rounded and otherwise injured cutting edges, which when run at economical speeds were likely at any minute to damage the finish of the work.

204 When one of these high speed tools is nearing its ruining point, a very trifling nick or break in the line of the cutting edge will be at once noticed by its making a very small but continuous scratch, projecting ridge, or bright streak, on the flank of the forging (namely, upon that part of the forging from which the spiral line of the chip has just been removed). When the skilled operator notices this line, he at once removes the tool from its cut, and notes upon the record "tool began to ruin"; the abbreviation for which in our case consists of the letters B R.

205 The letter R is used to indicate a tool which has been entirely ruined; the word "Good" (G) indicates a tool which is removed from the cut showing but very small damage or wear even to the lip surface; the word "Fair" (F) indicates a tool which shows considerable wear upon the lip surface, such, for instance as is shown in tool, Folder 3, Fig. 17d, the cutting edge of which has, however, not as yet absolutely started to ruin.

206 It is a curious fact that high speed tools which differ in their chemical compositions, and perhaps also slightly in their high heat and subsequent treatment, give very different indications while cutting that they have begun to ruin. For instance, the kind of scratch, shiny streak, or ridge, which on high speed tools made from one chemical composition would indicate the approach of the ruining point, may possibly be no indication of the approach of the ruining point if made by another type of high speed tool.

207 It is therefore necessary for the operator with each new batch of tools which are to be used in an experiment to absolutely ruin a number of these tools so as to be thoroughly familiar with that exact appearance of the flank of the forging which unquestionably indicates the approach of the ruining point. After the operator has assured

himself beyond doubt of this indication, it will not then be necessary for him to ruin each tool completely. The writer has in mind many instances, however, in which from the appearance of the scratches or shiny streaks, etc., on the flank of the forging, he was convinced that the tool was about to ruin, and in which the same tool continued to run for many minutes afterward, and even, in some cases, at an increase in cutting speed. In this element, then, as in all others, nothing must be taken for granted, everything must be proved.

208 In paragraphs 353 and 354 two other reasons for the cutting edges of tools giving out are referred to:

a the spalling off or crumbling away of the tool due to the pressure of the chip at its extreme cutting edge, as shown in Folder 6, Fig. 31a; and

b the spalling off or crumbling away of the extreme cutting edge due to the feeding pressure at this point, as shown in Folder 6, Fig. 31b.

209 As both of these types of yielding must be chiefly considered in their relation to the acuteness of the lip angle of the tool, we refer to them later in the paper.

HOW TO MAKE AND RECORD EXPERIMENTS

ART OF EXPERIMENTING DEFINED AS DETERMINING EFFECT OF VARYING ONE ELEMENT WHILE ALL OTHERS ARE HELD CONSTANT

210 In paragraph 55 (Part 1) we have broadly defined the art of experimenting on this subject as an attempt to hold uniform and constant all of the elements which affect the final results under investigation except the one variable which is being studied, while this one is systematically changed and its effect upon the problem carefully noted.

211 It is the necessity of holding these variables constant which makes all these experiments so difficult, causes the apparatus and forgings tested to be so large and expensive, and consumes perhaps four-fifths of the time of the experimenter. Time and again in our work it has required days and sometimes weeks to prepare for an experiment which, after we have succeeded in obtaining uniformity in all the elements has been made in a few days or hours.

212 A description of how to maintain uniformity of conditions is then virtually a description of the art of experimenting on cutting metals. The writer will, therefore, begin by explaining in detail the precautions which must be taken to secure this uniformity.

THE METAL WHICH IS TO BE CUT

213 In determining the effect which any one of the more important elements has upon the cutting speed,—such, for instance, as the effect of the feed or thickness of shaving upon the speed,—it is necessary to make many standard cuts of 20 minutes' duration in succession for each thickness of shaving, in order to find the exact speed at which the tool will be ruined at the end of 20 minutes, as described in paragraph 144. For this reason the information required for each thickness of shaving may cause hundreds of pounds of metal to be cut up into chips; and since in determining the law many different thicknesses of shaving must be experimented with, and the metal cut must be of uniform hardness, in order to obtain accurate results not only a large experimental forging is called for, but the metal throughout the forging must be as nearly as possible uniform.

214 We have finally adopted as the standard size of forging best suited for experiments a piece about 10 feet long by 24 inches in diameter and weighing about 15,000 pounds. For this purpose we prefer a forging made from a large ingot cast from a carefully melted heat of open hearth steel, and forged with a large reduction in the diameter so as to obtain as nearly as practicable uniform working of the metal throughout from the outside to the central portions of the forging. This forging in all cases requires thorough annealing, and in some cases an oil hardening previous to the annealing. Before using it, experimental standard tensile test bars should be cut from each end of the forging and broken so as to prove the uniformity of the metal, and, if necessary, the metal should be re-treated by tempering and annealing until it has been demonstrated through breaking a sufficient number of test specimens to be uniform.

215 Masses of cast iron upon which tools are to be tested should in all cases have their central portion cored out, so that the metal will be cooled from the center outward as well as from the outside inward, thus producing an annular ring of cast iron from three to four inches thick; which, if sufficient precautions are taken to insure regular cooling, will be comparatively uniform throughout. We have used annular masses of cast iron, made in this manner, of 24-inch diameter with 12-inch cores, 12 feet long; of 15-inch diameter, 10-inch cores, 8 feet long; of 13-inch diameter, 7 feet long; of 13-inch diameter, 9-inch cores, 10 feet long. On the whole, we have obtained the most uniform results from a casting of 24-inch diameter, 16-inch core, and 10 feet long, walls of casting 4 inches thick poured on end, since the central portion of the annular rings which were 6 inches in thickness were

very materially softer than the outer or inner portions of the ring. We have found it much more difficult to obtain sufficiently large and uniform masses of cast iron than of steel.

216 A large diameter is called for in both forgings and castings, not only for the sake of obtaining a large quantity of uniform metal, but also to avoid as far as possible the effect of chatter upon the tool, caused by the deflection of the work; and the writer wishes to emphasize the necessity for large masses of metal if the experimenter hopes for trustworthy results.

THE EXPERIMENTAL LATHE

217 The large and uniform forgings and castings required in investigating the laws affecting cutting tools call for a large and powerful lathe in which to make the experiments. This machine must be both large and powerful for various reasons.

218 (A) Our experiments necessitate the taking of cuts with coarse feeds and great depths of cut as well as those with fine feeds and shallow depths.

219 (B) In all experiments there must be a substantial surplus in the driving and feeding capacity of the machine beyond that which is directly used in taking the cut, so that when the time arrives for the tool to give out, the driving mechanism of the lathe shall be sufficiently powerful to completely grind away that portion of the tool which is cutting without overstraining the machine, and thus ruin the tool according to our standard referred to in paragraph 151.

220 (C) This ruining of the tool must be accomplished without either diminution of the speed of cutting or any material deflection or yielding either in the forging itself, in the driving mechanism of the lathe, or in the tool or the tool post and its supports; or in the feeding mechanism.

221 In brief, the lathe should be a much more powerful machine in all its elements than that which would be required in the daily process of taking cuts of the maximum sizes which are to be experimented upon.

THE SPEED CHANGES OF THE MACHINE

222 The lathe should be capable of running at any rate of cutting speed between the limits, say, of 3 and 300 feet per minute. This wide range of speeds is called for through the necessity of taking both light and heavy cuts upon metals in the two cases of extreme hardness and extreme softness. It is also particularly necessary that the

driving mechanism should be such as to maintain as nearly as possible a uniform cutting speed throughout the experiment, even though there may be very great variations in the driving power which is used during different parts of the same experiment.

223 To illustrate: In order to be certain that precisely the same cutting speed is maintained from the beginning to the end of our standard run of 20 minutes, it is necessary, after securing the tool in its proper position in the tool post, to bring its nose into the position which it should occupy in order to take the exact depth of cut which the experiment calls for. The speed of the lathe must then be accurately adjusted so that the precise number of feet per minute will be indicated by the "rotameter" when held against the surface of the forging, as described in paragraph 230, and the driving power and speed control of the lathe should be so uniform that when the feed motion of the lathe is thrown into action, the cutting speed of the tool will neither be appreciably increased nor diminished as the lathe changes suddenly from running without load to running under the full pressure of the cut.

THE FEEDING MECHANISM

224 Such gearing should be used in the feed motion as will insure absolute uniformity in the feed. On no part of the feed mechanism should apparatus be used which depends for its action upon friction, and the feed mechanism should be sufficiently large and massive not only to advance the tools when under the heaviest cut and when they are dull, without danger of breaking, but to be sure that the tool is advanced at an absolutely uniform rate, whatever may be the feed resistance which it must overcome. In other words, precisely the same uniformity in the rate of feed is demanded as in the rate of cutting speed, and the gearing should give as many positive changes in the thickness of the feed as practicable.

225 As referred to in paragraph 581, the feed gearing must be sufficiently powerful to produce a feeding pressure at the cutting edge of the tool equal to the maximum driving pressure.

THE WEIGHT OF THE MACHINE

226 It is also particularly desirable that all parts of the machine should be sufficiently massive to absorb the slight inequalities in the driving and feeding pressures caused both by the minute wavelike variations of the cutting resistance of the chip and any inequalities in the driving mechanism, without allowing these variations to show

themselves in the form of chatter in the tool. It is necessary, therefore, that the tool post and its supports as well as the lathe bed should be massive and wide.

THE BEST TYPE OF EXPERIMENTAL LATHE

227 As stated in paragraph 28, we have had at various times some ten different machines fitted up for the purpose of carrying on our experiments. Our best apparatus was that employed in the three years' experiments at the works of the Bethlehem Steel Company. A duplicate of this lathe and apparatus was used in the Paris Exhibition in 1900 in showing to the public the high speeds at which tools treated by the Taylor-White process could be run.

228 This apparatus is illustrated in Folder 9, Fig. 50; in which M represents a 40 horse power electric motor which is geared to E, a large and powerful pair of "Evans Tapered Friction Driving Pulleys," by means of which a speed variation of 1 to 4 can be obtained. B is the belt driving from one set of cone pulleys upon the Evans driving shaft down to the lathe cone pulleys C. From this cone pulley the power is either transmitted directly or through a double train of gears, G_1 and G_2, to the large geared face plate of the lathe, which is 62 inches in diameter. This lathe swings clear of the saddle, a forging 52 inches in diameter, and was designed especially heavy throughout its bed, saddle, head and tail stocks, for the purpose of taking heavy roughing cuts upon steel forgings.

229 The writer's object in illustrating this lathe is to advise future experimenters to adopt a mechanism throughout which is at least as massive and powerful as the one used by us. If, for example, the lathe mentioned in the Manchester experiments is examined, it will be seen that it is too small to admit a forging large enough in diameter to make the great number of tests upon metal of uniform quality which are necessary in any one of the series of experiments to determine the effect of the more important elements upon the cutting speed; such, for instance, as the effect on the cutting speed of varying the thickness of the chip or the depth of cut. And again, Professors Breckenridge and Dirks in the experiments made by them at the University of Illinois (published November 15, 1905), were so hampered by the size of the lathe at their disposal as to make it impossible to use test pieces of cast iron which contained enough metal to properly determine any of the laws.

MEASURING THE CUTTING SPEED

230 On Folder 9, Fig. 54, is shown in full size an instrument called a "rotameter," which we have found the best appliance for practical use in measuring the cutting speed. The small wheel *W*, which projects beyond the rim of the rotameter is firmly pressed directly against the surface of the rotating forging. The circumference of the small disk or wheel in the rotameter moves with the same velocity as the surface of the forging, and through gearing inside of the instrument rotates the two hands upon the face of the rotameter—corresponding to the hands of a watch—one of which points to the feet and the other to the inches of travel. In taking a reading with this instrument, its two hands are set at zero, and a stop-watch is started at the instant that the wheel of the rotameter is pressed upon the moving forging. The rotameter on being removed from the forging at the end of a minute indicates on its face the rate of cutting speed.

231 Owing to the direction in which the chip runs off of the tool, the rotameter can best be used upon the larger of the two diameters of the forging; and it is our custom to record the speed of the cut as the speed of the forging upon the larger of these two diameters.

232 It is necessary to accurately standardize each of these rotameters before using, and frequently afterward, to be sure that its hands indicate the exact distance the circumference of the wheel travels. This is done by measuring accurately on any smooth surface a distance of say 20 to 30 feet, and running the rotameter along this path by hand.

233 The speed of the forging should be checked by the rotameter at frequent intervals throughout the test, to be absolutely sure that it does not vary, and in all cases a record should be kept of the exact outside diameter of the forging together with the longitudinal distance which the tool travels in 20 minutes in the direction parallel to the axis of the work. These data enable the experimenter to accurately check the actual average cutting speed maintained throughout the test with the speed aimed at and recorded from the rotameter measurements.

234 On Folder 9, Fig. 53, is illustrated an instrument called the "cutmeter," which we have found useful and accurate in measuring cutting speeds. The circumference of the disc *W* is pressed against the surface of the forging whose speed is to be measured. An increase in the revolutions of the shaft to which this disc is attached causes a proportional increase in the force with which an annular mag-

net mounted on the same shaft as this disk tends to rotate another disc which forms an armature for this magnet. The rotation of this armature is controlled by an accurately standardized steel spring which tends steadily to bring it back to its zero position. The scale of the instrument, which gives the cutting speed directly in feet per minute, is mounted on the circumference of the armature disc, and is read opposite a fine wire in the middle of a glass covered opening in the body of the instrument. Like the rotameter, it must be checked up from time to time to be sure that it remains absolutely accurate.

235 This instrument would be perhaps, on the whole, the most satisfactory which we know of for measuring cutting speeds in experiments as well as for the daily shop use by machinists and foremen, were it not for the fact that the makers for some unaccountable reason have made the wheel *W* smaller than the body of the cutmeter. This defect renders it awkward to apply in all cases, and impossible for accurate use in many cases. It has, however, two very great advantages:

a no stop watch need be used;

b the exact cutting speed can be read on the scale of the instrument within a few seconds after it is in contact with the work.

236 As a check upon all mechanical appliances used in determining cutting speed, the speeds should be calculated by measuring the diameter of the forging and counting its revolutions per minute as obtained by making a chalk or other mark upon the circumference of the face plate of the lathe; and by means of a stop-watch noting the time required for the lathe to make a given number of revolutions, say ten or fifty, according to whether the speed is slow or fast. From this data the accurate cutting speed is figured, preferably by the use of a circular slide rule known as the "omnimeter."

237 At the end of each test we again calculate the actual average cutting speed obtained by ascertaining the average revolutions per minute. This is done by dividing the total travel of the lathe carriage in inches by the thickness of the feed and the number of minutes; and having accurately measured the diameter of the work, the cutting speed is quickly figured by the use of an omnimeter.

MEASURING THE DEPTH OF THE CUT

238 Before starting a 20-minute run, the experimenter should assure himself by accurately calipering the forging that the portion of the test piece about to be cut is of uniform diameter throughout the distance to which the cut will extend. The writer would especially

call attention to the error which we at first made, and which he believes has been made by all other experimenters, of attempting to measure the depth of the cut and maintain it uniform throughout the experiment by using calipers. It is out of the question to accurately caliper the forging while it is running at the high speed required for the cut, and with the jar incident to this work, and calipers should only be used on the forging while it is at rest.

239 On Folder 9, Fig. 55, is illustrated a "cut gage" which we have used for maintaining uniform the depth of the cut; a separate gage similar to this is made for each depth of cut to be experimented with.

240 The longer edge of this gage is placed upon the larger diameter of the forging, while the shorter edge, or offset, rests at the same time upon the smaller diameter. By placing it upon the forging in such a position that the light back of it shows between the edge of the gage and the forging, the depth of the cut can be maintained with great accuracy.

241 We look upon a gage of this sort as an absolute necessity for maintaining accuracy in this work. An examination of the records of other experimenters will show the necessity of this instrument, as they almost invariably record in one column the depth of the cut which they wish to have, and in another column the depth of the cut which they succeed in maintaining.

242 It is of course a very simple matter before starting on the experiment to turn the smaller diameter on the forging so as to give any exact depth of cut which may be wanted. If, however (after turning the desired smaller diameter), the nose of the tool is then brought so that it is barely in contact with this surface, the instant that the feed is thrown in for the experimental run and the tool starts to cut, the pressure of the shaving will invariably either force its nose slightly further away from the axis of the forging or else draw it a little closer to it and in this way give a shallower or greater depth of cut than that desired.

243 As before explained, calipering while the forging is running is too inaccurate to enable the operator to readjust the tool so as to again obtain the exact depth of cut, whereas through the use of the cut gage illustrated, the tool can at any time be accurately advanced a little closer to the axis of the forging or drawn away from it, until the exact depth of cut aimed at is attained.

244 The first move, then, on the part of the operator, after starting his tool on a 20-minute run is to exactly readjust the depth of his cut through the use of the cut gage, and he should next

immediately use the rotameter, or the cut meter in checking the cutting speed. A trifling variation either in the depth of cut or in the cutting speed does not affect the ultimate result of the experiment, provided these variations occur during the first two or three minutes while the tool is warming up and before it has reached its maximum heat. A very slight variation, however, either in the depth of cut or in the cutting speed will be likely to spoil the whole experiment if it occurs, say, after the first two or three minutes of the run. The depth of cut should be checked at least once every two minutes throughout the experiment with the cut gage and oftener as the tool approaches the ruining point.

ON UNIFORMITY IN THE CUTTING TOOLS

245 The greatest difficulty met with in experimenting is to insure uniformity in all of the cutting tools which are used in a given series of experiments made, say, for the purpose of determining one of our laws. There are many elements which affect the standard speed at which a tool will just be ruined at the end of a 20-minute run; and in preparing a lot of tools for an experiment, it is not only essential for the experimeter to assure himself that in the making of each tool every precaution has been taken with one element after another to secure uniformity; but, in addition to this, it is necessary to prove by actually running each one in a preliminary tool test that they are all uniform, say, within a limit of about 2 per cent.

246 To go into further detail on this point, the following precautions should be taken for securing uniformity in the tools: (The writer refers here particularly to cutting tools made by the Taylor-White process, which have come to be called almost universally tools made from the "new tool steels."[1])

247 Special precaution should be taken in buying the tool steel from which these experimental tools are to be made, to be sure that it is of uniform quality. The very best and most uniform make of tool steel should be purchased, and the maker should be informed of the important use to which this particular lot of tools is to be put, and should be requested to take special care in mixing and melting the steels to be sure that they are uniform in their chemical composi-

[1] The expression "new tool steels" is absolutely misleading, since the novelty lies in heating these tools to the melting point or nearly so, and in the other heat treatments explained in the Taylor-White patents, and not in their chemical composition; because tool steels which were appropriate to this treatment were sold in the market long before Mr. White and the writer discovered that high speeds could be obtained through heating them to the high heat. "High heat tools" or "modern high speed tools" describes them much better.

tion, and subsequently in the hammering and annealing of the bars. A chemical analysis either of each bar, or, at least, of the heat of steel from which the bars are forged, should be made. The same care should be taken in the dressing and subsequent heat treatment of each of the tools to see that they are all alike. It is of special importance that the tools should be ground slowly, and that a very heavy stream of water should be directed throughout the operation of grinding directly upon the cutting edge of the tool, so as to absolutely avoid the danger of overheating the tool at the cutting edge in grinding, as described in paragraph 473. More high speed tools are daily injured in our machine shops through overheating in grinding than in any other way, and this injury is all the more serious because it can only be detected after the tool has been used in the machine by its failure to run at the proper speed.

248 The tools must be ground so that they have noses of the same size; so that the curve or contour of the cutting edge is of exactly the same shape in each tool; and so that the clearance and lip angles are all alike. It is entirely possible for a skilled grinder, with the use of especially made gages, to grind all of these tools to their proper shapes by hand on an ordinary grindstone or emery wheel,[1] but this process is exceedingly slow and requires a good deal of skill.

249 If practicable, therefore, the tools should all be ground with an automatic tool grinder having a "former" of the exact shape of the cutting edge. The writer has found it desirable, however, in almost all cases, in preparing a set of experimental tools, to appoint an inspector to stand over the man who was running the automatic grinder to absolutely assure himself that these tools were ground without the danger of overheating; and also, in spite of the work being done on an automatic grinder, this inspector should examine each tool with templets and gages to be certain that the curves and angles are right.

250 Before using a tool, the operator himself should see to it that the bottom surface of the tool is a true plane, and that the tool is supported by the tool post as far forward as practicable (in fact, almost directly under the cutting edge), thus eliminating one possible element of vibration or chatter. In many cases we have, therefore, found it advantageous to grind the bottom of our experimental tools to a true plane on a surface grinder.

[1] The writer himself, in his early experiments, spent days in grinding his experimental tools to the right shapes, and it was this experience which first led him to appreciate the necessity for an automatic tool grinder in a machine shop, and then to design one and put it into use.

251 After all of these precautions have been taken, it is then necessary to accurately determine the standard speed at which this make of tool will be ruined at the end of a 20-minute run, and if, for example, it has been shown that the standard ruining speed of these tools is 61 feet per minute when run upon a forging which has been previously proved to consist of uniform metal, then each of the tools before being used in experimenting should be successively run upon the same forging at a speed of 60 feet for a period of 20 minutes without ruining.

WHERE PRACTICABLE IN EXPERIMENTING NO CUTS LIGHTER THAN $\frac{3}{16}$ INCH DEPTH BY $\frac{1}{16}$ INCH FEED SHOULD BE TAKEN

252 In determining many of the laws connected with this art it is possible for the experimenter to choose the size of the cut to be used in his trials, and we should recommend for all experiments of this character the use of a cut $\frac{3}{16}$ of an inch in depth by $\frac{1}{16}$ of an inch feed. If a heavier cut than this be taken, too much of the test piece (either forging or casting) will be used up, and there is likely to be difficulty in obtaining sufficient test metal of uniform quality to complete a full set of experiments. On the other hand, with a depth less than $\frac{3}{16}$ of an inch, the error that is likely to be made even by the best experimenters in maintaining a uniform depth of cut, becomes such a large percentage of the total depth as to materially affect the accuracy of the experiment. This is true to such an extent that as a result of our experience we should consider practically worthless for determining laws all cuts that are as shallow as $\frac{1}{16}$ of an inch, and we should much prefer a $\frac{3}{16}$ inch depth to a $\frac{1}{8}$ inch depth.

253 A feed which is finer than $\frac{1}{16}$ of an inch is also undesirable for experiments because any trifling imperfection or flaw at or near the cutting edge of the tool will more seriously affect the results with a smaller feed than this, and also small hard spots or other blemishes in the metal that is being tested have a much worse effect upon the tools with fine than with coarse feeds.

MORE TIME REQUIRED IN PREPARATION THAN IN EXPERIMENTING

254 From all this it is evident that the time and trouble required in preparing for a set of experiments is far greater than that of actually doing the work; and this should emphasize the necessity for great care in every detail both of making the experiments and in accurately observing and recording every item which may have any bearing upon the final result.

255 Let me again repeat, then, that the art of making these experiments consists mainly in holding constant and uniform all the various elements affecting the problem, while the one element which is being studied is varied.

256 We have been fully alive for some seven or eight years past to the necessity for all these precautions, and the writer believes himself to be justified in saying that no care has been spared in doing our work. Yet in critically examining the results of even our more recent sets of experiments, it becomes apparent that for one cause or another, perhaps more than one-half of the results obtained were such that we should not be willing to accept them as true indications of the laws which we were investigating; and in most of these cases of what may be called partial failure we have not been able to definitely locate the cause. At times it was probably due to a slight irregularity in the composition of the tool steel, or perhaps to a brittleness at the cutting edge of some of the tools which did not show in our preliminary tests of the tools, and in other cases to occasional zones or spots in the experimental forging which were harder than the rest, or to an undetected variation in the rate of the cutting speed; all of which merely emphasizes the necessity for taking infinite pains in this work.

ON RECORDING THE DETAILS AND RESULTS OF EXPERIMENTS

257 In describing our experiments no effort will be made to give them in their chronological order. As before stated, between 30,000 and 50,000 experiments have been made by us, so that it is entirely out of the question to publish in a paper of this sort a record of the original observations made upon the runs of each of the experimental tools. It would be foolish, in fact, to publish any such voluminous record. Each of the sets of experiments undertaken by us were made for some one specific purpose, and as soon as practicable after completion, the important runs of the tools were copied in groups from the original records upon summary sheets, each group of standard cuts having a bearing upon some one of the items to be investigated. It would be improper in a paper of this sort, however, to publish even all of these sheets of summaries. But in order that our methods of originally recording and then grouping and finally summarizing our experiments may be clearly understood, the writer has decided to publish certain sample sheets from each of these records.

OPERATOR'S DAILY RECORD

258 On Folder 11, Fig. 77, is given a sample of one of our sheets, upon which were entered by the operator the details of the experiments made at the lathe. It may be remarked that no possible harm is done by recording too many items even remotely affecting each test, while the omission of what may at the time seem a matter of no moment may ultimately prove of most serious import. The writer has particularly in mind the fact that in some of his early experiments he failed to either date his experimental sheets or to number consecutively his experiments. Owing to this omission he was obliged later on to throw away all of the results obtained because he was unable to distinguish between the records of a certain set of experiments which he knew to have been accurately made, and another set in which he discovered, after making, a serious error in method.

SUMMARY SHEET

259 On Folder 8, Fig. 45, is shown a sample of one of our summary sheets, upon which have been recorded the runs of one of our best series of experiments for the purpose of determining the effect of feed and depth of cut in cutting steel with a round nosed tool.

260 On Folder 11, Fig. 77, is shown a sample of one of our summary sheets, upon which have been recorded the runs of one of our best series of experiments for the purpose of determining the effect of feed and depth of cut in cutting cast iron with a round nosed tool.

261 On Folder 11, Fig. 75, is shown a sample of one of our summary sheets, upon which has been recorded another set of experiments for the purpose of determining the laws of feed and depth of cut in cutting steel with a round nosed tool. This set of experiments represents a case in which we have made a partial failure in our work. In fact, it represents one of the poorest of any of our sets of experiments from which we have attempted to draw conclusions. By examining the standard speeds of the tools under the column marked $\frac{9}{32}$ inch depth of cut, it will be observed that the standard speeds in this column are approximately the same as those given for the $\frac{3}{16}$ inch depth of cut. Now, our knowledge of the art teaches us that without question the true cutting speed for a $\frac{9}{32}$ inch depth of cut should be materially slower than that for a $\frac{3}{16}$ inch depth of cut. It follows, therefore, that we have failed at some point in making these experiments. In this particular case the failure may have been due either to irregularity in the standard tools, or more probably to a

change in the hardness of the forging operated upon, as we approached its central zone.

262 On Folder 15, Fig. 103, is shown a sample of one of our summary sheets, upon which has been recorded a set of experiments for the purpose of determining the effect of the duration of the cut upon the standard cutting speed, cuts of 10, 20, 40, and 80 minutes' duration each being experimented with. This set of experiments likewise belongs to the class of those which show a certain amount of irregularity, either in the forging, the tools, or in our methods. (See further comments upon the cuts of 10 minutes' duration in paragraph 703.)

EACH LAW AND DIAGRAM THE RESULT OF SEVERAL SERIES OF EXPERIMENTS

263 In finally determining and formulating what we believe to be the true laws, no one set of experiments was found to be sufficient. In almost all cases the results obtained by two or more sets of experiments were plotted together upon logarithmic paper, and by inspecting the lines drawn through the points located upon this logarithmic paper, the results of several sets of experiments can be coördinated, and the general trend of the law much better indicated than would be possible from any one set of experiments alone. A mathematical expression is then found which corresponds to the line which approximates most closely to the law, as indicated by thus combining several experiments. For a sample of this use of a logarithmic sheet, see Folder 16, Fig. 115.

264 On Folder 16, Fig. 114, will be again seen a sample of the actual curve corresponding to one of these mathematical expressions, and each of the spots located at various places close to the line of this curve represents the summary or conclusion arrived at as the result of a large number of experiments.

265 An inspection of these curves will indicate the extent to which we have succeeded in a mathematical representation of the laws.

266 These matters will be discussed more fully later in the paper, our object in anticipating being to give at this point a birdseye view, as it were, of a number of the steps taken toward finally making daily use of our experiments through the slide rules.

PROPER SHAPE FOR STANDARD SHOP TOOLS

267 As stated in paragraph 1 (Part 1) of this paper, our principal object in carrying on the investigation has been to obtain the knowledge required in fixing daily a definite task, with a time limit, for each machinist. It is evident that this involves the use of standard cutting tools throughout the shop which are in all respects exact duplicates of one another.

A FEW CAREFULLY CONSIDERED TYPES OF TOOLS BETTER THAN GREAT VARIETY

268 In our practical experience in managing shops we have found it no easy matter to maintain at all times an ample supply of cutting tools ready for immediate use by each machinist, treated and ground so as to be uniform in quality and shape; and the greater the variety in the shape and size of the tools, the greater becomes the difficulty of keeping always ready a sufficient supply of uniform tools. Our whole experience, therefore, points to the necessity of adopting as small a number of standard shapes and sizes of tools as practicable. It is far better for a machine shop to err upon the side of having too little variety in the shape of its tools rather than on that of having too many shapes. And the energy of the department for maintenance of tools should be directed rather toward securing an ample and uniform supply of tools limited to a few shapes than to a great variety. The writer can hardly lay too much stress upon this point and it, therefore, becomes all the more important to use the greatest care and judgment in selecting the standard shape which is to be used for roughing tools.

STANDARD TOOLS ILLUSTRATED

269 In Folder 5, Figs. 20a to 25e, are illustrated the shapes of the standard tools which we have adopted, and in justification of our selection the writer would state that these tools have been in practical use in several shops both large and small through a term of years, and are giving general, all-round satisfaction. It is a matter of interest also to note that in several instances changes were introduced in the design of these tools at the request of some one foreman or superintendent, and after a trial on a large scale in the shop of the suggested improvements, the standards as illustrated above were again returned to. These shapes may be said, therefore, to have stood the test of extended practical use on a great variety of work.

270 It would seem to be of such great importance to explain fully our reasons for adopting these tools as our standards, that the writer will describe in the pages immediately following a number of the experiments, the results of which have perhaps had the greatest influence in determining the curve or line of the cutting edge. With this end in view, it has been found necessary to record these experiments out of the order and the place in this paper in which they would otherwise be properly and logically described. These remarks refer particularly to experiments described in paragraphs 292 to 306.

CONFLICT BETWEEN THE DIFFERENT OBJECTS TO BE ATTAINED IN CUTTING METALS WHICH AFFECT THE DESIGN OF STANDARD TOOLS

271 Our standard tools may be said to represent a compromise in which each one of the elements given in paragraph 272 has received most careful consideration, and has had its due influence in the design of the tool; and it can also be said that hardly a single element in the tools is such as would be adopted if no other element required consideration.

272 The following, broadly speaking, are the four objects to be had in mind in the design of a standard tool:

a The necessity of leaving the forging or casting to be cut with a true and sufficiently smooth surface;

b removing the metal in the shortest time;

c the adoption of that shape of tool which shall do the largest amount of work with the minimum combined cost of grinding, forging, and tool steel;

d ready adaptability to a large variety of work.

273 As we go further into this subject the nature of the conflict between these four objects and of the sacrifice which each element is called upon to make by one of the others will become apparent. To illustrate the nature of these compromises:

274 Generally speaking, we have been obliged to adopt as our standard shape a tool which can be run at only about, say, five-eighths of the cutting speed which our knowledge of the art and our experiments show us could be obtained through another tool of entirely different shape if no other element than that of cutting speed required consideration.

275 We have been obliged to sacrifice cutting speed to securing smaller liability to chatter; a rather truer finish; a greater all-round convenience for the operator in using the tool; and a comparatively

cheaper dressing and grinding. The most important of the above considerations, however, is the freedom from chatter.

276 On the other hand, we have been obliged to adopt a rather more elaborate and expensive method of dressing the tools than is usual in order to provide a shape of tool which allows it to be ground a great many times without redressing, and also in order to make a single Taylor-White heat treatment of the tool last longer than it otherwise would. And again, the shape of the curve of the cutting edge of the tool which we have adopted—first, to insure against chatter, and second, for all-round adaptability in the lathe,—calls for much more expense and care in the grinding than would be necessary if a more simple shape were used. This necessitates in a shop either a specially trained man to grind the tools by hand to the required templets and angles or preferably the use of an automatic tool grinder.

277 Before describing in detail the considerations which led to the adoption of our standard tools, it will be necessary to explain some of the more important experiments which have a direct bearing upon this subject. The shape of our standard tools will be again treated in paragraphs 325 to 332.

ELEMENTS AFFECTING CUTTING SPEED OF TOOLS IN THE ORDER OF THEIR RELATIVE IMPORTANCE

278 The cutting speed of a tool is directly dependent upon the following elements. The order in which the elements are given indicates their relative effect in modifying the cutting speed, and in order to compare them, we have written in each case figures which represent, broadly speaking, the ratio between the lower and higher limits of speed as affected by each element. These limits will be met with daily in machine shop practice.

279 (A) The quality of the metal which is to be cut; *i. e.*, its hardness or other qualities which affect the cutting speed.
Proportion is as 1 in the case of semi-hardened steel or chilled iron to 100 in the case of very soft low carbon steel.

280 (B) The chemical composition of the steel from which the tool is made, and the heat treatment of the tool.
Proportion is as 1 in tools made from tempered carbon steel to 7 in the best high speed tools.

281 (C) The thickness of the shaving; or, the thickness of the spiral strip or band of metal which is to be removed by the tool, measured while the metal retains its original density; not the thickness of the actual shaving, the metal of which has become partly disintegrated.

Proportion is as 1 with thickness of shaving $\frac{3}{16}$ of an inch to $3\frac{1}{2}$ with thickness of shaving $\frac{1}{4}$ of an inch.

282 (D) The shape or contour of the cutting edge of the tool, chiefly because of the effect which it has upon the thickness of the shaving.

Proportion is as 1 in a thread tool to 6 in a broad nosed cutting tool.

283 (E) Whether a copious stream of water or other cooling medium is used on the tool.

Proportion is as 1 for tool running dry to 1.41 for tool cooled by a copious stream of water.

284 (F) The depth of the cut; or, one-half of the amount by which the forging or casting is being reduced in diameter in turning.

Proportion is as 1 with $\frac{1}{2}$ inch depth of cut to 1.36 with $\frac{1}{8}$ inch depth of cut.

285 (G) The duration of the cut; *i. e.*, the time which a tool must last under pressure of the shaving without being reground.

Proportion is as 1 when tool is to be ground every $1\frac{1}{2}$ hours to 1.207 when tool is to be ground every 20 minutes.

286 (H) The lip and clearance angles of the tool.

Proportion is as 1 with lip angle of 68 degrees to 1.023 with lip angle of 61 degrees.

287 (J) The elasticity of the work and of the tool on account of producing chatter.

Proportion is as 1 with tool chattering to 1.15 with tool running smoothly.

288 A brief recapitulation of these elements is as follows:

(A) quality of metal to be cut: 1 to 100;

(B) chemical composition of tool steel: 1 to 7;

(C) thickness of shaving: 1 to $3\frac{1}{2}$;

(D) shape or contour of cutting edge: 1 to 6;

(E) copious stream of water on the tool: 1 to 1.41;

(F) depth of cut: 1 with $\frac{1}{2}$ inch depth to 1.36 with $\frac{1}{8}$ inch depth of cut;

(G) duration of cut: 1 with $1\frac{1}{2}$ hour to 1.20 with 20-minute cut;

(H) lip and clearance angles: 1 with lip angle 68 degrees to 1.023 with lip angle of 61 degrees;

(J) elasticity of the work and of the tool: 1 with tool chattering to 1.15, with tool running smoothly.

289 The quality of the metal which is to be cut is, generally speaking, beyond the control of those who are in charge of the machine shop, and, in fact, in most cases the choice of the hardness of metals to be used in forgings or castings will hinge upon other considerations which are of greater importance than the cost of machining them. This subject will be further treated in paragraph 1129.

290 The chemical composition of the steel from which the tool is made and the heat treatment of the tool will, of course, receive the most careful consideration in the adoption of a standard tool. No shop, however, can now afford to use other than the "high speed tools," and there are so many makes of good tool steels, which, after being forged into tools and heated to the melting point according to the Taylor-White process, will run at about the same high cutting speeds, that it is of comparatively small moment which particular make of high speed steels is adopted. This subject will be further dealt with in paragraph 965, etc.

EFFECT OF THICKNESS OF SHAVING ON CUTTING SPEED THE MOST IMPORTANT SUBJECT FOR EXPERIMENT

291 It is the THICKNESS OF SHAVING, then (item C in the list above) which must be first considered, as this element has more effect upon the design of our standard tools, and in fact upon the whole problem of cutting metals than any other single item which is completely under the control of those who are managing a shop.

EXPERIMENTS SHOWING EFFECT UPON CUTTING SPEED OF VARYING THE THICKNESS OF THE SHAVING, A TOOL WITH STRAIGHT-EDGE BEING USED, REMOVING A SHAVING IN ALL CASES EXACTLY ONE INCH LONG

292 The following experiments were made to determine the effect upon the cutting speed of varying the thickness of the shaving. For this purpose a number of broad nosed tools with straight cutting edges, similar to that shown in Folder 7, Fig. 35, were forged from ordinary tempered carbon tool steel. Straight cutting edges were used in order that the shaving should be of the same thickness throughout. The corner of the tool, however, which cuts at the smaller of the two diameters of the forging was rounded to a radius of exactly $\frac{1}{8}$ of an inch. This was necessary in order to thin the shaving down sufficiently at this point to absolutely insure that part of the tool which gives the required smoothness to the forging from giving out before the tool dulls along the straight line of the cutting edge.

293 In these experiments the tool was set in the lathe as shown in Folder 16, Fig. 111, so that exactly one inch of the STRAIGHT PORTION of the cutting edge was at all times under pressure of the shaving. In all cases a feed of 8/100 of an inch was used, so that the thickness of the shaving was in each case directly proportional to the depth of the cut.

294 These experiments were made upon a forging of the following chemical composition:

Carbon	0.369 per cent
Manganese	0.517 per cent
Silicon	0.238 per cent
Phosphorus	0.043 per cent
Sulphur	0.051 per cent

Tensile test bars actually cut from the body of the forging showed the following physical properties:

Tensile strength	82.947 lbs.
Stretch	21.50 per cent
Contraction of area	30.00 per cent

295 A heavy stream of water was thrown throughout the experiments upon the shaving just at the spot at which it was being removed from the forging by the tool.

296 Depths of cut of exactly $\frac{1}{8}$, $\frac{3}{16}$, $\frac{1}{4}$ and $\frac{3}{8}$ inch were used, corresponding to thicknesses of shaving of 0.01, 0.015 0.02 and 0.03 inch.

297 The speeds corresponding to these cuts, each of which was of 20 minutes' duration, are given in Folder 16, Table 113. These cutting speeds are plotted on Folder 16, Figs. 114 and 115, and a curve corresponding to the following formula is drawn approximately through these various points. They are also plotted on logarithmic paper, on Folder 16, Fig. 113, on which the speed points lie approximately in a straight line.

$$V = \frac{1.54}{t^{\frac{1}{3}}}$$

in which

V = cutting speed in feet per minute for 20-minute cut;

t = thickness of shaving in inches.

298 On Folder 16, Table 113, will be seen also the ratio between the cutting speeds of each of these thicknesses of shaving, from which it will be noted, for example, that by dividing the thickness of the shaving by 3, the cutting speed is increased in the ratio of 1 to 1.8. For further description of these experiments, see paragraph 761.

EXPERIMENTS SHOWING EFFECT UPON CUTTING SPEED OF VARYING THE DEPTH OF THE CUT, A TOOL WITH STRAIGHT-EDGE BEING USED, REMOVING IN ALL CASES SHAVING 0.03 INCH THICK

299 Tools of the same shape as those shown in Folder 7, Fig. 35, were set in the exact position shown in Folder 17, Fig 35, and in Folder 17, Fig. 116, we show in section lines the sizes and proportions of the chips, so that with a feed of 0.08 inch the tool in all cases removed a shaving 0.03 inch thick. The experiments were made upon the same forging, and with otherwise exactly the same conditions as those described just above for determining the effect of thickness of shaving upon cutting speed. Such depths of cut were used as to bring consecutively $\frac{1}{2}$ inch, $\frac{3}{4}$ inch and 1 inch in length of the straight portion of the cutting edge under the shaving.

300 These experiments were made upon a forging of the following chemical composition:

Carbon	0.492 per cent
Manganese	0.477 per cent
Silicon	0.194 per cent
Phosphorus	0.042 per cent
Sulphur	0.039 per cent

301 Tensile test bars actually cut from the body of the forging show the following physical properties:

Tensile strength	97,719 lbs.
Stretch	.15 per cent
Contraction of area	.23.2 per cent

302 The cutting speeds corresponding to these three depths of cut are given on Folder 17, Table 117. These speeds are plotted on Folder 17, Fig. 119, and a curve corresponding approximately to the following formula is drawn through these various points. They are also plotted on logarithmic paper, on Folder 17, Fig. 118, on which the speed points lie approximately in a straight line.

$$V = \frac{12.22}{L^{\frac{1}{n}}}$$

in which

V = cutting speed in feet per minute for 20-minute cut;

L = length of shaving in inches.

303 On Folder 17, Table 117, will also be seen the ratio between the cutting speeds of each of these depths of cut, from which it will be

noted, for example, that by dividing the length of the cutting edge by 3, the cutting speed is increased in the ratio of 1 to 1.27.

304 Attention is called to the fact, however, that with round nosed tools as the depth of cut becomes more shallow, there is a greater increase in the cutting speed than in the case of tools having straight line cutting edges, because, as explained in paragraphs 307 and 311, with a round nosed tool the thickness of the shaving becomes thinner and thinner as the extreme nose of the tool is approached. In the case of round nosed tools, therefore, when the depth of the cut is diminished, the cutting speed is increased for two entirely different reasons:

First, because the chip bears upon a smaller portion of the cutting edge of the tool, and

Second, because the average thickness of the chip which is being removed is thinner in the case of round nosed tools with a shallow depth of cut than it was with the deeper cuts.

305 To make it more apparent that the element affecting the cutting speed the most is the thickness of the shaving, the writer would call attention to the fact that dividing the thickness of the shaving by 3 increases the cutting speed in the ratio of 1 to 1.8, while dividing the depth of the cut by 3 only increases the cutting speed in the ratio of 1 to 1.27.

306 From these ratios it will be seen that the thickness of the chip has about three times as great an effect in modifying the cutting speed as has the depth of the cut. For further description of these experiments, see paragraph 761.

PRINCIPAL OBJECT IN HAVING THE CUTTING EDGE OF TOOLS CURVED IS TO INSURE AGAINST DAMAGE TO THE FINISHED SURFACE OF THE WORK

307 The above experiments described in paragraphs 293 to 303 upon the effect of thickness of shaving on cutting speed enable us to explain from the theoretical standpoint the well known fact that each properly designed roughing tool should have the line or contour of its cutting edge curved as it approaches the extreme nose of the tool or that portion of the tool which insures a good and true finish of the work. A tool whose cutting edge forms a curved line of necessity removes a shaving which varies in its thickness at all parts. The only type of tool which can remove a shaving of uniform thickness is one with a straight line cutting edge. The object in having the line of

the cutting edge of a roughing tool curved as that part of the cutting edge which does the finishing is approached, is to thin down the shaving at this point to such an extent as will insure the finishing part of the tool remaining sharp and uninjured even although the main portion of the cutting edge may have been ruined through overheating or from some other cause.

308 The effect of a curved cutting edge upon the thickness of the shaving will be seen by inspecting Folder 16, Fig. 112, in connection with Figs. 111, 113, 114, and 115.

309 On Folder 15, Fig. 112, is shown a view of the curved cutting edge of a tool enlarged to 16 times its full size; thus at points 0.005, 0.01, 0.02, and 0.04 inch on this curve, the shaving is enlarged in each case so as to be respectively just 16 times as thick as the shavings shown in Fig. 111, shavings 0.005, 0.01, 0.02, and 0.04 inch.

310 It will be observed that the quality and accuracy of the finish left upon the work will depend upon maintaining sharp and uninjured throughout the cut that portion of the cutting edge of the tool which extends, say, from about point 0.005 inch to point 0.02 inch.

311 By examining the standard cutting speeds noted opposite each of the straight-edge shavings, Fig. 111, it will be seen that the standard or ruining speed at point 0.04 inch, for instance, on the curve of our enlarged tool, is 13 feet. From this it is evident, then, that if the tool enlarged in Fig. 112 were run at a cutting speed of 13 feet per minute so as to just ruin it at point 0.04 inch, the tool at point 0.01 inch would then be running at less than one-half of the cutting speed which would be required to ruin it. It would be, therefore, well within its safe limit of cutting speed, and would remain sharp and uninjured until the edge at 0.04 inch had entirely broken down. It is obvious then that a curved line cutting edge insures the finishing part of the tool from damage and for this reason the cutting edges of all tools should be curved, at least as that portion of the edge of the tool is approached which leaves the work of the proper size and with the proper finish.

TOOLS WITH BROAD NOSES HAVING FOR THEIR CUTTING EDGES CURVES OF LARGE RADIUS BEST TO USE EXCEPT FOR RISK OF CHATTER

312 Upon appreciating the increase in the cutting speed obtained through thinning down the shaving, as shown in our experiments with straight cutting edge tools, described in paragraphs 292 and 303, the tools shown on Folder 7, Figs. 32, 33, and 34, were made, and

used on roughing work for years in the axle lathes of the Midvale Steel Company. The gain in cutting speed of these standard broad nosed tools over our standard round nosed tool, as shown in Folder 5, Figs. 24 and 23, is in the ratio of 1.30 : 1.

313 This general shape of tool continues to be extensively used, but it is subject to the disadvantage that it is likely to cause the work to chatter, and so leave a more or less irregular finish.

314 Were it not for this difficulty, added to the fact that our standard round nosed tool has a greater all-round adaptability and convenience, the tools illustrated on Folder 7, Figs. 32 to 34, would undoubtedly be the proper shapes for shop standard. This matter will be further discussed in paragraph 665. A method is there described of using two or more broad nosed tools so as to be free from danger of chatter even upon work which is especially liable to chatter.

REASONS WHY CUTTING EDGE WITH COMPARATIVELY SMALL RADIUS OF CURVATURE TENDS TO AVOID CHATTER

315 The avoidance of chatter in the tool plays such an important part in the design of the curve of the cutting edge for standard shop tools that we quote in full from that portion of Dr. Nicolson's admirable experiments which appears to the writer to offer an explanation for one of the important causes for chatter.

316 Dr. Nicolson's experiments, which were made with special apparatus (of his own design) for weighing the pressure of the chip upon the tool, were described in his paper (published in Transactions, Vol. 25, pp. 672, 673, 674), as follows:

317 The experiments (numbered 725 to 732 inclusive), the results of which are given in Table 9 are of special interest in regard to: First, the variation of the cutting force as the cut progresses at a very low speed; second, the variation of the cutting stresses with large ranges of speed variation.

318 These experiments were made with a tool having a 55 degree cutting and a 67½ degree plan angle; a cut ⅜ inch deep by ⅛ inch wide being taken.

319 For numbers 725 and 726 the lathe was turned round at a cutting speed of about 1 foot in 5 hours, by means of a wire rope made fast round the large cone pulley, and hauled upon by a man operating a winch.

320 A pointer about 5 feet long was clamped upon the forging, and the four dynamometer gages were read at every half an inch of motion of the end of this pointer, *i. e.*, at about six one-hundredths (0.0625) of an inch of the cut. The vertical force varies from 9080 to 8920 every ⅜ of an inch of motion of the tool, the same wave length characterizing the variation of the surfacing and traversing forces. The observations have been plotted in Fig. 340 [see Folder 12, Fig. 86, present paper] on a base of actual relative tool motion.

321 A similar experiment, No. 636, carried out with the first dynamometer, is shown in Fig. 341. [See Folder 12, Fig. 82, present paper.] Here the cut was heavier, $\frac{3}{8}$ inch by $\frac{1}{4}$ inch, and the tool had a 45 degree plan, and 60 degree cutting angle. The wave length of the force-curve is about 0.6 inch for this experiment, and it varies between 13,000 and 8000 pounds. It will be observed that the force attains a maximum soon after the cutting commences to crack or shear across, and that it drops to a minimum when the small piece of cutting falls off the forging. At such a slow speed as this the cutting has time to shear off right across in separate fragments, whereas it forms a continuous curl of considerable rigidity when the cutting speed is higher than a few feet per minute. These fragments measured, in this experiment, about $\frac{1}{4}$ inch across the widest part of their surface next the top of the tool in the direction of motion.

322 In these experiments Dr. Nicolson cuts the metal at a speed of one foot in five hours. By referring to Folder 12, Fig. 82, (Fig. 341, of his paper) it will be seen that the pressure on the tool increases and diminishes in the ratio of about 8 to 13 at comparatively regular wave-like intervals, and by comparing this diagram with Folder 12, Fig. 86 (Fig. 340 of his paper) in which a thickness of feed only one-half as great is used, it will be seen that the wave lengths are in this case very much shortened. From this it appears that each thickness of shaving has its own corresponding wave length for the periods of maximum and minimum pressure on the tool.

323 Since the thickness of the shaving is uniform with straight edge tools, it is evident that the period of high pressure will arrive at all points along the cutting edge of this tool at the same instant and will be followed an instant later by a corresponding period of low pressure; and that when these periods of maximum and minimum pressure approximately correspond to or synchronize with the natural periods of vibration either in the forging, the tool, the tool support, or in any part of the driving mechanism of the machine, there will be a resultant chatter in the work. On the other hand, in the case of tools with curved cutting edges, the thickness of the shaving varies at all points along the cutting edge, as we have pointed out in paragraphs 292 and 303. From this fact, coupled with Dr. Nicolson's experiments, it is obvious that when the highest pressure corresponding to one thickness of shaving along a curved cutting edge is reached, the lowest pressure which corresponds to another thickness of shaving at another part of the cutting edge is likely to occur at about the same time, and that therefore variations up and down in pressure at different parts of the curve will balance or compensate one for the other. It is evident, moreover, that at no one period of time can the wave of high pressure or low pressure extend along the whole length of the curved cutting edge.

324 Dr. Nicolson's experiments afford us a much needed theoretical explanation of what has for years been a well recognized fact, namely, that tools with straight cutting edges are much more likely to chatter than those with curved edges, and if Dr. Nicolson's apparatus and experiments had given no further information than this, they would be well worth all of the trouble and time expended upon them.

REASONS FOR ADOPTING THE PARTICULAR CURVES CHOSEN FOR THE CUTTING EDGES OF OUR STANDARD TOOLS

325 Having explained the necessity for curved cutting edges in standard roughing tools, it is desirable to give our reasons for the adoption of the particular curves of our standard tools, illustrated in Folder 5, Figs. 20a to 25e, and Folder 17, Fig. 120. It will be noted that as the body of the tool becomes smaller, the radii of curvature of the cutting edge also become correspondingly smaller. This change in the curve of the cutting edge is rendered necessary by the fact that the smaller tools are used in the small lathes, which, generally speaking, work upon small forgings, from which cuts are removed which are both shallow in depth and have comparatively fine feeds. Forgings which are small in diameter are quite as liable to chatter as the larger forgings which are machined in larger lathes, and in order to avoid this chatter, it is necessary that a curve for the cutting edge should be chosen which will give a variation relatively in the thickness of shaving even in small depths of cut. Thus, for the avoidance of chatter, the curve of the cutting edge should be small in proportion as the depth of cut and feed which it it normally takes are small.

326 As will be seen later, the smaller radius of curvature of the cutting edge involves a diminution in cutting speed. Therefore, with larger sized tools it becomes important, on the other hand, to take as large a radius of curvature for the cutting edge as is compatible with freedom from chatter. The coarser feed which usually accompanies the larger tool also calls for a larger radius of curvature at the nose of the tool, in order that the ridges left by the spiral path of the tool along the forging shall be as low as practicable.

327 The all-round adaptability of the standard tool to a variety of uses also calls for a smaller radius of curvature the smaller the tool, since standard roughing tools are continually required to run up against a shoulder or into a corner on the work, and the fillet in this corner is normally small in proportion as the forging or casting is small.

328 Generally speaking, also round nosed roughing tools of the type shown do not require the special care in adjusting in the tool post that would be demanded of tools designed with a straight line cutting edge for the purpose of producing a smooth finish, etc.

329 By comparing curves of the tools on Folder 5, Fig. 21a, with Folder 5, Fig. 21b, it will be observed that tools which are to be used for cutting cast iron and hard steel have slightly larger radii of curvature than those which are to be used for the softer steel and wrought iron. The reason for this change is that much slower cutting speeds must be used in cutting hard steels than for soft, and this is also to a less degree true for cast iron as compared with soft steel.

330 It is a matter of common experience that the slower the cutting speed, the less the liability of the tool to chatter. It therefore becomes safe from the standpoint of chatter to use in cutting hard steel and also cast iron a larger radius of curvature than would be permissible in cutting soft steel. The fact has already been pointed out that the larger the radius of curvature, the thinner the shaving, and therefore the higher the cutting speed, and in the interest of economy, it is of course particularly desirable in cutting hard steels to increase the necessarily slow cutting speed as much as practicable.

331 For the following entirely different reason, also, the radius of curvature for tools to be used in cutting cast iron is made larger than in tools to be used in cutting soft steel. Cast iron is cut, as will be seen in paragraphs 491 and 512, with less cutting pressure or resistance to the tool than is required for soft steel. Therefore, in a given lathe a greater depth of cut and coarser feed can be taken on cast iron than on soft steel; and, as explained above, the coarser the feed, the greater should be the radius of curvature of the extreme nose of the tool in order to leave an equally smooth finish.

332 In many machine shops a very considerable portion of the work consists of cuts to be taken upon pieces of cast iron; the depth of the cut being comparatively shallow and the strength and rigidity of the casting begin so great that in order to use even approximately the full pulling power of the lathe or planer, etc., broad feeds must be taken. In our standard shop tools, as illustrated in Folder 5, Fig. 21a, the extreme end of the noses are rounded with too small radii to take a very broad feed, and yet at the same time leave a reasonably smooth finish. It is therefore desirable in all such shops to have standard tools available which are especially designed for work of this character.

333 In Folder 5, Fig. 22, is illustrated a single size of the type of tool which we recommend for this purpose. It will be observed

that in form it corresponds exactly to our other standard tools for cutting cast iron and hard steel except that the extreme nose of the tool is widened out so as to have a curve of very large radius, approximating to a straight line.

LIP AND CLEARANCE ANGLES OF TOOLS

334 Contrary to the opinion of almost all novices in the art of cutting metals, the clearance angle and the back slope and side slope angles of a tool are by no means among the most important elements in the design of cutting tools, their effect for good or evil upon the CUTTING SPEED and even upon the pressure required to remove the chip being much less than is ordinarily attributed to them.

CLEARANCE ANGLE OF THE TOOL

335 The following are our conclusions regarding the clearance angle of the tool.

a For standard shop tools to be ground by a trained grinder or on an automatic grinding machine, a clearance angle of 6 degrees should be used for all classes of roughing work. (See paragraphs 336 to 340)

b In shops in which each machinist grinds his own tools a clearance angle of from 9 degrees to 12 degrees should be used. (See paragraph 339)

336 In seeking for the proper clearance angles for tools, we have as yet been unable to devise any type of experiment which would demonstrate in a clear cut manner (as, for example, the experiments cited for lip angles in paragraphs 361 and 367) which clearance angle is the best. The following, however, are the considerations which affect the choice of clearance angles.

337 On the one hand, it is evident that the larger the clearance angle, the greater will be the ease with which the tool can be fed (wedged or driven) into its work, the first action of the tool when brought into contact with the forging being that of forcing the line of the cutting edge into the material to be cut. On the other hand, every increase in the clearance angle takes off an equal amount from the lip angle, and therefore subjects the tool to a greater tendency to crumble or spall away at the cutting edge, as indicated on Folder 6, Figs. 31a and 31b. It must be remembered also that the tool travels in a spiral path around the work which it is cutting in the lathe, and

that the angle of this path with a perpendicular line in the case of coarse feeds taken upon small diameters of work becomes of distinctly appreciable size. In all cases, therefore, the clearance angle adopted for standard shop tools must be sufficiently large to avoid all possibility from this source of rubbing the flank of the tool against the spiral flank of the forging. The clearance angles for roughing tools in common use vary between 4 degrees and 12 degrees. We have had experience on a large scale in different shops with tools carefully ground with clearance angles of 5 degrees, 6 degrees and 8 degrees. In the case of one large machine shop which had used clearance angles ground to 8 degrees through a term of years, they finally adopted the 6 degrees clearance angle with satisfaction. For many years past our experiments have all been made with the 6 degree clearance angle, and this has been demonstrated to be amply large for our various experiments. On the other hand, a 5 degree clearance angle in practical use in a large shop has appeared to us through long continued observation to grind away the flank of the tool just below the cutting edge rather more rapidly than the 6 degrees angle. We have, therefore, adopted the 6 degrees clearance angle as our standard.

A CLEARANCE ANGLE OF FROM 9 TO 12 DEGREES SHOULD BE USED IN SHOPS IN WHICH EACH MACHINIST GRINDS HIS OWN TOOLS

339 It should be noted, however, that in shops systematized by us the cutting tools are invariably ground either on an automatic tool grinder, or by special men who are carefully taught the art of grinding and provided with suitable templets and gages, and that in this case the clearance angle for every tool is accurately made to 6 degrees.

340 In shops, however, in which each lathe or planer hand grinds his own tools, a larger clearance angle than 6 degrees should be used, say, an angle of from 9 degrees to 12 degrees, because in such shops in nine cases out of ten the workmen grind the clearance and lip angles of their tools without any gages, merely by looking at the tool and guessing at the proper angles; and much less harm will be done by grinding clearance angles considerably larger than 6 degrees than by getting them considerably smaller. It is for this reason that in most of the old style shops in which the details of shop practice are left to the judgment of the men or to the foreman, that clearance angles considerably larger than 6 degrees are generally adopted.

LIP ANGLE OF THE TOOL

341 The following are the conclusions arrived at regarding the angles at which tools should be ground:

342 (*A*) For standard tools to be used in a machine shop for cutting metals of average quality: Tools for cutting cast iron and the harder steels, beginning with a low limit of hardness, of about carbon 0. 45 per cent, say, with 100,000 pounds tensile strength and 18 per cent stretch, should be ground with a clearance angle of 6 degrees, back slope 8 degrees, and side slope 14 degrees, giving a lip angle of 68 degrees. These angles are used in the tools illustrated on Folder 5, Figs. 21a and 25e. (See paragraphs 358 to 359)

343 (*B*) For cutting steels softer than, say, carbon 0.45 per cent having about 100,000 pounds tensile strength and 18 per cent stretch, tools should be ground with a clearance angle of 6 degrees, back slope of 8 degrees, side slope of 22 degrees, giving a lip angle of 61 degrees. These angles are used in tools illustrated in Folder 5, Fig. 25b. (See paragraph 361)

344 (*C*) For shops in which chilled iron is cut a lip angle of from 86 degrees to 90 degrees should be used. (See paragraph 365)

345 (*D*) In shops where work is mainly upon steel as hard or harder than tire steel, tools should be ground with a clearance angle of 6 degrees, back slope 5 degrees, side slope 9 degrees, giving a lip angle of 74 degrees. (See paragraph 360)

346 (*E*) In shops working mainly upon extremely soft steels, say, carbon 0. 10 per cent to 0. 15 per cent, it is probably economical to use tools with lip angles keener than 61 degrees. (See paragraphs 368 to 370)

347 (*F*) The most important consideration in choosing the lip angle is to make it sufficiently blunt to avoid the danger of crumbling or spalling at the cutting edge. (See paragraphs 352 to 356)

348 (*G*) Tools ground with a lip angle of about 54 degrees cut softer qualities of steel, and also cast iron, with the least pressure of the chip upon the tool. The pressure upon the tool, however, is not the most important consideration in selecting the lip angle. (See paragraphs 374 and 367)

349 (*H*) In choosing between side slope and back slope in order to grind a sufficiently acute lip angle, the following considerations, given in the order of their importance, call for a steep side slope and are opposed to a steep back slope:

a With side slope the tool can be ground many more times without weakening it; (See paragraphs 379)

b The chip runs off sideways and does not strike the tool posts or clamps. (See paragraph 380)

c The pressure of the chip tends to deflect the tool to one side, and a steep side slope tends to correct this by bringing the resultant line of pressure within the base of the tool, as explained in paragraph 382.

d Easier to feed. (See paragraphs 383 and 384)

350 (I) The following consideration calls for at least a certain amount of back slope. An absence of back slope tends to push the tool and the work apart, and therefore to cause a slightly irregular finish and a slight variation in the size of the work. (See paragraph 386)

351 (J) For conclusions as to clearance angle, see paragraph 335.

352 Before it is possible to discuss the proper lip angles for tools, two ways in which the cutting edge gives out should be described.

353 On Folder 6, Fig. 31a, is shown on an enlarged scale the manner in which the sharp end of the wedge of the tool spalls off or crumbles away, when the lip surface of the tool right at the cutting edge is subjected to great pressure. In pars. 516 to 519, later in the paper, it will be pointed out that in the case of cutting very hard metals and also in cutting all qualities of cast iron, the pressure of the chip is concentrated very close to the line of the cutting edge, and the harder the metal to be cut and the smaller its percentage of extension, the greater will be the concentration of the pressure close to this line, and the greater will be the tendency of the cutting edge to spall off or crumble away.

354 On Folder 6, Fig. 31b, is shown another way in which the metal of the lip surface of the tool spalls off or crumbles away when the line of the cutting edge of the tool is subjected to great pressure in feeding or forcing the tool into the forging. In this case the hardness of the metal into which the tool is being fed is the chief element causing this type of injury to the cutting edge.

MOST IMPORTANT CONSIDERATION IN CHOOSING LIP ANGLE IS TO MAKE IT SUFFICIENTLY BLUNT TO AVOID DANGER OF CRUMBLING OR SPALLING OFF AT THE CUTTING EDGE

355 In deciding upon the acuteness of the lip angle of a tool the absolute necessity of guarding against the spalling or crumbling of the cutting edge from both of the foregoing causes becomes by far the most important of all considerations. In this connection the essential fact to be borne in mind is that the harder the metal to be cut, the

blunter must be the lip angle of the tool. In the case of chilled iron and semi-hardened steel, for instance, the lip angle must be made from 86 degrees to 90 degrees. A smaller angle than this will cause the metal at the extreme cutting edge to spall off or crumble away (quite as much on account of the feeding pressure as from the pressure of the chip) and thus ruin the tool. As the metal to be cut grows softer, however, the lip angle can be made keener without danger of spalling, until with standard tools intended to cut the softer steels, say with a high limit for hardness of about 100,000 pounds tensile strength and 14 per cent to 18 per cent stretch, the smallest lip angle which, in our judgment, it is on the whole wise to use would seem to be about 61 degrees.

356 Dr. Nicolson with his dynamometer experiments (see Figs. 328 and 329 of his paper) has shown that with a "cutting angle" of 60 degrees, corresponding to a lip angle of 54 degrees, clearance angle 6 degrees, tools remove metal with the minimum of pressure. This is also corroborated in a general way by our observations in cutting dead soft steel, referred to in paragraphs 368 to 370. Therefore from the standpoint of pressure, with a view to taking the largest cut with a given pulling power and with the least strain upon the working parts of the lathe, this angle should be approached. And although, on the whole, the question of pressure on the tool has less weight than either the crumbling at the cutting edge, the cutting speed, or the proper angles for obtaining the longest life and the largest number of grindings for a given tool, still it must be considered; and it is this which has led us to choose for our standard in each case THE KEENEST CUTTING ANGLE WHICH IS FREE FROM DANGER OF SPALLING.

357 As pointed out in paragraph 372, we belive that experiments would demonstrate the advisability of using still more acute lip angles for cutting dead soft steels.

358 Metals which even approach in hardness chilled iron and semi-hardened steel are but seldom met with in ordinary shop practice and, therefore, in selecting the lip angles for standard shop tools, we have divided the metals to be cut in a shop into two classes:

a cast iron and the harder classes of steel, say, beginning as a low limit for hardness with a steel of about 0.45 to 0.50 per cent carbon, 100,000 pounds tensile strength and 18 per cent stretch; and

b the softer classes of steel.

359 Our guiding principle in selecting the lip angles for the tools to be used in cutting cast iron and the harder classes of steel has been to select what we believe to be the smallest or most acute lip angle

which can be safely depended upon to run without danger of spalling off at the cutting edge while cutting the harder steels ordinarily met with in machine shop practice (such as the hardest steels used in this country for car wheel tires, say of 135,000 to 140,000 pounds tensile strength, and 9 to 10 per cent of stretch, and, for instance, unannealed tool steels, or the harder of the oil hardened and annealed forgings which are used under government specifications for making large steel cannon, etc.); and after large experience in cutting metals of this quality we have concluded that it would be unsafe to use a more acute lip angle than that shown on Folder 5, Fig. 20a, namely, a lip angle of 68 degrees, with clearance angle of 6 degrees, side slope of 14 degrees and back slope of 8 degrees. We have demonstrated by repeated trials that tools with the above lip angle are safe from danger of spalling or of crumbling at the cutting edge, even when cutting tire steel, gun steel or tool steel.

360 For shops which are engaged mainly in cutting steels as hard as tire steel, we should recommend as a standard tool one having 6 degrees clearance, 5 degrees back slope and 9 degrees side slope, giving a lip angle of 74 degrees. Since for this special work the tools can be run at a high cutting speed, they can be ground in less time and they can be ground more times for each dressing in the smith shop than tools with more acute lip angles.

361 The following experiment was made in 1906 with a high speed tool of the latest and best composition. The chemical composition of the tool was that of tool No. 1 in Folder 20, Table 128.

362 Repeated trials with the same tool ground first with a clearance angle of 6 degrees, back slope of 5 degrees, and side slope of 9 degrees, giving a lip angle of 74 degrees; and afterwards with a clearance angle of 6 degrees, back slope of 8 degrees, and side slope of 14 degrees, giving a lip angle of 68 degrees. No difference was indicated in the cutting speed of these two tools when used upon the very hard forging referred to in Folder 20, Table 128.

363 It is interesting, however, to note that machinists who grind their own tools and who are accustomed to machining hard tires and metals of the classes above referred to, invariably use a blunter lip angle than our standard of 68 degrees. After making a few mistakes by grinding tools with lip angles which are too acute, they are sure to lean too far toward the safe side, and adopt lip angles which are not quite sharp enough. They are influenced in this very largely, however, by the fact pointed out in paragraph 124 that the less acute the lip angle, the easier it is and the less time it requires to grind a tool.

A tool with a lip angle of 80 degrees for example, can be more easily ground than one with a lip angle of 70 degrees.

364 In those shops which work upon metals of average hardness and in which the tools are furnished to the machinists ground to the required shapes, and in which either automatic tool grinders are used or special grindstone men are employed to grind the tools, more work can be gotten out by grinding the tools to angles at least closely approximating ours than from the use of tools with blunter lip angles.

365 The reason for preferring the more acute lip angle of 68 degrees, for cutting medium hard metals to the angle of 75 degrees to 85 degrees adopted by the average machinist, is that the more acute angle removes the metal with a lower dressure on the tool (see paragraph 374); while repeated experiments made by us in cutting medium hard steels indicate that there is little if any difference in cutting speed between the 68 degrees lip angle and coarser angles. Our standard tools, therefore are capable of taking heavier cuts than the blunter tools, and in a given machine working to the limit of its pulling power, can remove rather more metal in a given time.

WHY TOOL FOR CUTTING SOFT CAST IRON SHOULD HAVE BLUNTER LIP ANGLE THAN TOOL FOR CUTTING SOFT STEEL

366 It may be a matter of surprise to some that we have adopted a lip angle of 8 degrees for cutting the softer grades of cast iron, while we recommend a lip angle of 61 degrees for the softer steels. It is one of the strange anomalies met with in so many of the elements of this art, however, that if we experiment with a very soft cast iron, on the one hand, and a very soft steel, on the other—the standard cutting speeds of which are each, say, 150 feet per minute with a $\frac{3}{16}$ inch depth of cut and $\frac{1}{16}$ inch feed—in the case of the soft steel the highest speed can be obtained only with a cutting edge at least as keen as 61 degrees, and we believe even keener, while the lip angle corresponding to the highest cutting speed with soft cast iron is 68 degrees or even blunter. The following experiments were carefully made and have since been verified by repeated trials.

367 In 1894 before the discovery of high speed cutting tools, the standard speed for cutting soft cast iron was determined for each of two sets of tools, one set having a lip angle of 61 degrees and the other 68 degrees. These tools were made from tempered carbon steel of $\frac{7}{8}$ inches by $1\frac{3}{8}$ inch section, having the curve of the cutting edge as shown in standard, Folder 5, Fig. 24. One set was ground with 6 degrees clearance angle, 8 degrees back slope, and 14 degrees side slope, thus giving a lip angle of 68 degrees. The other set was ground with

a clearance angle of 6 degrees back slope of 8 degrees, and side slope of 22 degrees, thus giving a lip angle of 61 degrees. These two sets of tools were successively run on a carefully standardized test piece of soft cast iron of about 24 inches diameter. The standard ruining speed of the 68 degrees angle was 67 feet, while the standard ruining speed of the 61 degrees lip angle was 65½ feet; thus in cutting soft cast iron, changing the lip angle from 68 to 61 degrees reduced the cutting speed from 67 to 65½ feet, a loss of 2.3 per cent in speed.

368 On the other hand, the following result was obtained repeatedly in experiments made in 1900 upon a carefully standardized test forging made of soft steel, whose chemical composition and physical properties were about:

Carbon	0.105 per cent
Manganese	0.25 per cent
Silicon	0.008 per cent
Sulphur	0.04 per cent
Phosphorus	0.008 per cent
Chromium	0.047 per cent
Tensile Strength	48,000 pounds
Elastic Limit	24,500 pounds
Extension	39 per cent
Contraction of Area	62 per cent

Taylor-White treated tools of the chemical composition of tool steel No. 27 on Folder 21, Table 139, were used. Body of the tool, $\frac{7}{8}$ by $1\frac{3}{8}$ inch, curve of the cutting edge, shown in Folder 5, Fig. 24, with a clearance angle of 6 degrees, back slope 12 degrees, side slope 18 degrees, giving a lip angle of about 61 degrees. The standard ruining speed with a $\frac{3}{16}$ inch depth of cut and a $\frac{1}{16}$ inch feed was 150 feet per minute; tools in other respects exactly like these, except that the back slope was 8 degrees and the side slope 14 degrees (giving a lip angle of 68 degrees), showed in repeated trials a ruining speed of from 125 to 130 feet.

369 The effect of changing the lip angle from 68 to 61 was to increase the cutting speed from 125 to 150 feet, a gain of 20 per cent. Thus a more acute cutting angle used on a tool for cutting soft steel produces just the opposite effect from that produced in cutting equally soft cast iron.

370 The lip angle of 68 degrees used in cutting soft steel, when tried at the high speed of 150 feet, caused the chip to be much more distorted or upset, and thickened, and after running a short time at this speed, the chip began to stick to the lip surface of the tool almost as though it were welded. With the more acute angle of 61 degrees this

bunching up of the chip and welding did not occur. It was also evident that when the chip began to weld to the lip of the 68 degree tool, the power required to cut the metal was so greatly increased as in a number of cases to entirely stall or slow down the lathe, whereas with the 63 degrees lip angle, the lathe was never slowed down in the least. At slower cutting speeds it was not noticeable that the 68 degrees tool consumed any more power than the 63 degrees tool.

371 It would be interesting to repeat this experiment at the very high speed with a dynamometer, carefully measuring the pressure of the chip on the tool.

372 The writer believes that it would be profitable to experiment with more acute lip angles than 61 degrees in cutting dead soft steel such as above referred to, containing about 0.10 per cent carbon, and of 48,000 pounds tensile strength, which approximates to wrought iron. It may be that with this extremely soft steel still higher cutting speeds could be obtained with more acute angles, in which case it would be advisable of course to make special tools for cutting this quality of metal in shops where large amounts of it are used. However, a trial of this sort would not modify our selection of 61 degrees for the standard angle for cutting the ordinary softer steels met with in the average machine shop, because as explained above, our standard shop tools for cutting the softer steels are intended for use in cutting metals with an upper limit of hardness of about carbon 0.45 to 0.50, say, 100,000 pounds tensile strength, 18 per cent of stretch or thereabouts, and if a more acute lip angle than, say, 61 degrees were used in cutting steel of this hardness, there would be danger of the cutting edge crumbling away or spalling off.

THEORY AS TO WHY AN ACUTE LIP ANGLE PRODUCES A HIGHER SPEED FOR CUTTING SOFT STEEL AND A SLOWER SPEED FOR SOFT CAST IRON

373 In all matters pertaining to this art a theoretical explanation of the various phenomena is of less importance than a clear knowledge of the facts. However, it may still be of interest, at least, to present our theory as to the opposite effects of an acute lip angle in the case of soft cast iron and soft steel.

374 Dr. Nicolson in his dynamometer experiments has demonstrated the fact that tools ground with a "cutting angle of 60 degrees" which corresponds to a "lip angle of 54 degrees" work with a smaller total pressure upon the tool than tools whose cutting angles are either larger or smaller than 54 degrees, the metals upon

which he experimented being as follows: Medium cast iron, which with a $\frac{3}{16}$ inch depth of cut and a $\frac{1}{16}$ inch feed having a standard speed of 49 feet per minute; and steel 60,000 pounds tensile strength and 26 per cent extension, having a standard speed of 111 feet per minute with a $\frac{3}{16}$ inch depth of cut and $\frac{1}{16}$ inch feed. His experiments, however, show that although tools of these angles cut with less pressure, yet tools with larger angles can be run at higher cutting speeds. This confirms our experiments on cast iron as cited above in paragraph 367. The reason for this phenomenon appears to be as follows:

375 First, the amount of heat generated by the friction of the chip is doubtless closely proportional to the pressure of the chip upon the tool. Therefore, with the 54 degrees cutting angle and its lower pressure there will be less heat generated than with the larger cutting angles. On the other hand, the heat is carried away from the cutting edge mostly through the metal of the tool itself (very little heat being radiated into the air); and the more acute the angle of the tool, the smaller will be the cross-section of the wedge shaped metal of the tool close to the cutting edge, so that the blunter angled tools will have also a larger section of metal for carrying away the heat. In addition to this, and of greater importance in our judgment, is the fact that in cutting cast iron the pressure of the chip comes very close to the cutting edge of the tool, as explained in paragraph 523, and the more acute its angle, the more will a trifling amount of wear or damage affect the cutting edge. These two causes working together operate to enable the blunter cutting edge to run at higher speeds in cutting cast iron. On the other hand, as pointed out in paragraphs 170 and 516 above, the pressure of the chip in cutting dead soft steel comes at a considerable distance from the cutting edge, so that in this case the more delicate edge of the acute angled tool is further removed from the source of heat and also subject to much less abrasive wear than in cutting cast iron; and the cross-section of the tool beneath the center of pressure of the chip is much larger. Therefore, in the case of very soft steel we have exactly the reverse effect, as described in paragraph 368, namely, the more acute their lip angles down to 61 degrees (the low limit experimented with by us), the higher the cutting speeds at which tools can be run.

WHY TOOLS SHOULD BE GROUND WITH GREATER SIDE SLOPE THAN BACK SLOPE

376 We have endeavored above to make it clear that the paramount consideration affecting the choice of the lip angle for standard tools has been the avoidance of the danger of spalling or crumbling

at the cutting edge. Having chosen a lip angle which is sufficiently blunt to avoid danger from this cause, it must still be decided whether this angle shall be produced, say, altogether by side slope or altogether by back slope, or by a combination of side slope and back slope; and in settling this question there are several important, and, as usual, conflicting considerations. These may be divided into the following groups, which are given in the order of their importance:

a Ease and cheapness of grinding and the effect of repeated grindings upon the strength and life of the tool;

b guiding the chip in the proper direction for convenience in operating;

c the effect of pressures produced by side slope and back slope upon the tendency of the tool to gouge or plunge either forward or sideways;

d the power required to feed.

377 In the following brackets are grouped these several considerations, in the order of their relative importance, as they affect favorably or unfavorably the adoption of a steep side slope:

IN FAVOR OF STEEP SIDE SLOPE

a With side slope tool can be ground many more times without weakening it;

b chip runs off sideways and does not strike tool post or clamps;

c less tendency to force and deflect the tool to one side as it tends to bring resultant line of pressure within base of the tool, as explained in paragraph 382;

d easier to feed.

AGAINST STEEP SIDE SLOPE

a Danger of gouging or plunging into the work greater.

378 And in the following brackets are also grouped the same considerations as they affect favorably or unfavorably a steep back slope:

IN FAVOR OF STEEP BACK SLOPE

a Does not push tool and work away from one another.

AGAINST STEEP BACK SLOPE

a Grinds down into body of tool and weakens tool and allows fewer grindings for given height of tool;

b in case of gouging, the work is more apt to be spoiled through tool plunging forward as it does with steep back slope than if it plunges sideways as it does with steep side slope;

c runs chip directly back against tool, tool post or clamp;

d harder to feed.

SIDE SLOPE AND BACK SLOPE AS AFFECTED BY THE GRINDING

379 On Folder 7, Figs. 39a and 39b, we show the side view of two tools, in both of which views the lip angle of the tool is 61 degrees. In the case of Folder 7, Fig. 39b, the lip angle is attained entirely through back slope and Folder 7, Fig. 39b, and Folder 5, Fig. 20b (standard tool for cutting soft steels), there is 8 degrees of back slope and 22 degrees of side slope. The cutting edges of both of these tools are of the same height. An inspection of the drawings will show, however, that the tool with all back slope can be ground but comparatively few times before the corner of the grindstone will begin to cut away the body of the tool, thus weakening it, and allowing a comparatively small number of grindings before the tool is redressed, while at the same time making the grinding much more expensive, as explained in paragraphs 435 to 439.

SIDE SLOPE AND BACK SLOPE AS THEY AFFECT THE DIRECTION OF THE CHIP

380 With the modern high speeds used in cutting steel the disposition of the chip becomes a matter of no small moment, and in many cases it is absolutely necessary in designing the tool to provide against the jamming of the chip either between a portion of the tool itself and the lip surface of the tool, or between the nose of the tool and the clamps or tool post which hold it.

381 It is evident that a steep back slope tends to throw the chip either directly against the tool or against the tool post or clamps, while a steep side slope guides the chip off to one side, and this therefore becomes one of the most important reasons for adopting a steep side slope.

THE TENDENCY OF THE PRESSURE OF THE CHIP TO BEND THE TOOL TO ONE SIDE

382 In pars. 417 to 425, relating to the dimensions of the steel to be used in the body of the tool, will be seen the desirability of keeping the resultant line of pressure of the chip upon the tool within or as near as possible to the base of the tool. Dr. Nicolson's experiments

(Fig. 336 of his paper) show that the side pressure of the chip upon the tool diminishes as the cutting angle becomes more acute and reaches a minimum with an angle of 60 degrees. Therefore a steep side slope will tend to keep the resultant line of pressure within the base of the tool.

THE EFFECT OF SIDE SLOPE AND BACK SLOPE UPON THE POWER REQUIRED TO FEED THE TOOL

383 The diagram in Fig. 336 in Dr. Nicolson's paper also indicates the desirability of a steep side slope even to the extent of 30 degree in diminishing the power required to feed.

384 A tool ground with a slope of 30 degrees offers a resistance to feeding of but 1 per cent to 10 per cent while a tool ground with a 15 degrees slope meets with a feeding resistance equal to from 12 per cent to 20 per cent of the total pressure on the tool.

385 For further discussion of feeding resistance, see paragraph 581.

BACK SLOPE NEEDED TO SECURE BETTER FINISH AND GREATER ACCURACY IN SIZE

386 A study of all of the above elements would lead to the conclusion that tools should be designed with all side slope and no back slope. There is, however, one element which makes it desirable to have a certain amount of back slope; namely, the fact that a steep back slope diminishes the tendency of the chip to push the tool and the work away from one another, and it is evident that the greater the pressure tending to force the tool and the work apart, the greater will be the irregularity in the finish left by the nose of the tool upon the work. This irregularity both in size and finish is particularly noticeable in those cases in which the tool and its supports are not especially rigid, and in which the depth of the cut varies from one part of the forging to another; and also when the surface of the forging is more or less eccentric or uneven owing to the irregularities left by the hammer in forging.

387 In paragraph 217 special attention has been called to the necessity for great rigidity in all parts of the lathe to be used in experimenting. There are a few important elements, however, which can only be studied through the use of a lathe in which the supports for the tool are more or less yielding, and even somewhat loose rather than rigid. These elements are:

a the tendency of the tool to gouge or plunge into the work; and

b the forcing of the tool and the work apart.

388 It is evident that the effect of the acuteness of the angle of slope of the tool is directly opposite in these two cases. The more acute the angle of slope, the greater the tendency to gouge, and the less the tendency to push the work and the tool apart. It may be said that in well managed machine shops the tool supports will be properly adjusted so as to avoid any lost motion or looseness, and that therefore the tendency to gouge from this cause should not be considered. The fact is, however, that we are dealing with shops as they are, and even in many of the best shops, machines will be found whose tool supports are entirely too springy and more or less less worn or out of proper adjustment. We have made repeated careful experiments with lathes having springy tool supports and with more or less lost motion, and in such machines, providing the tool is fastened tight in the tool post, we have found that the tools ground to our standard angles, shown on Folder 5, Figs. 20a and 20b, very rarely gouge or plunge forward or sideways seriously. The danger of plunging forward, however, has been one of the reasons influencing the adoption of a back slope as small as 8 degrees.

389 The tendency of the tool and work to push apart, on the other hand, is very marked with tools designed with all side slope and no back slope. A series of experiments was tried with a set of tools, in the one case having 6 degrees clearance, 8 degrees back slope, 14 degrees side slope; and in the other case, a set having 6 degrees clearance, a back slope of minus 5 degrees, or more properly a forward slope of 5 degrees; and a side slope of 25 degrees. The lip angle of the first of these sets being 68 degrees, while the lip angle of the second was about the same. One of the principal reasons for comparing these types of tools was that the tool when ground with 5 degrees front slope makes what is known as a shearing cut and that a shearing cut has the special advantage of leaving a smoother finish.

390 The standard speeds of these two tools were found through accurate experiments to be practically the same, there being less than 1 per cent difference between the two in favor of the 8 degrees back slope. With these tools, however, even when used in a lathe with a comparatively rigid and a tight and well adjusted tool support, there was a most noticeable difference in the tendency to push the tool and the work apart. With heavy cuts a much smoother and better finish was left by the tool with the 8 degrees back slope in spite of the shearing effect of the other tool; and it was evident to all of those who watched the experiment that the tool with back slope was greatly to be preferred to the other. It may add weight to understand that this particular experiment was made at the request of the superintendent

and foreman of a large machine shop in which tools ground with the 5 degrees front slope had formerly been standard. These men, however, were completely convinced through watching the two types of tools working under exactly uniform conditions.

FORGING AND GRINDING TOOLS

ON THE SHAPE OF TOOLS AS AFFECTED BY GRINDING AND FORGING

391 The following are the important conclusions arrived at upon this subject:

392 (A) The shapes into which tools are dressed and the ordinary methods of dressing them are highly uneconomical, mainly because they can be ground only a few times before requiring redressing. (See paragraphs 431 to 441)

393 (B) The tool steel from which the tool is to be forged should be one and one-half times as deep as it is wide. (See paragraphs 420) The standard length for tools will be found in Folder 6, Table 27. (See paragraph 428)

394 (C) To avoid the tendency of the tool to upset in the tool post under pressure of the cut, the cutting edge and the nose of the tool should be set well over to one side of the tool. (See paragraph 422)

395 (D) Tool builders should design lathes, boring mills, etc., with their tool posts set down lower than is customary below the center of the work. (See parargaph 426)

396 (E) In choosing the shape for dressing a tool, that shape should be given the preference in which the largest amount of work can be done for the smallest combined cost of forging and grinding.

397 (F) Forging is much more expensive than grinding, therefore the tool should be designed so that it can be ground:

a the greatest number of times with a single dressing; and

b with the smallest cost each time it is ground. (See paragraph 431)

398 (G) Best method of dressing a tool is to turn its end up high above the body of the tool. (See paragraph 442) Tools can be entirely dressed by this means in two heats. For detailed steps in forging a tool by this method see:

a heating (see paragraphs 447 to 460);

b bending (se aragraph 450);

c drawing down the heel (see paragraph 454);
d shaping with the chisel (see paragraph 456);
e cutting correct height and lip angle (see paragraph 458)
f setting over to one side (see paragraph 459).

399 (H) Importance of carefully heating the tool for dressing. (see paragraphs 447 to 449);

400 (J) Fire or heat cracks in tools are due to the following causes:

a seams or internal cracks in bar of tool steel. (See paragraph 461);
b nicking and breaking the bar of tool steel while it is cold. (See paragraphs 445 and 463);
c failing to turn the tool over and over while heating it for forging. (See paragraph 464);
d too rapid heating, particularly at the start, in a hot fire. (See paragraphs 466 to 468);

401 (K) It is of great importance to properly adjust the relative amount of work to be done in the smith shop and on the grinding machine in making the tool.

a too much work is generally done in dressing tools to exact shape in the smith shop, particularly when automatic grinding machines are used. (See paragraph 470)
b A limit gage should be used by the smith to properly regulate the proportion of smith work and grinding work in making the tool. (See paragraph 471)

ON GRINDING TOOLS

402 The following are the important conclusions arrived at with reference to grinding tools:

403 (A) More tools are ruined in every machine shop THROUGH OVER HEATING IN GRINDING than from any other cause. (See paragraphs 473 and 1016)

404 (B) The most important consideration is how to grind tools rapidly without overheating them. (See paragraph 473)

405 (C) To avoid overheating, a stream of water amounting to five gallons per minute should be thrown, preferably at a slow velocity, directly on the nose of the tool where it is in contact with the emery wheel. (See paragraph 473)

406 (D) To avoid overheating where tools are ground by hand or with an automatic tool grinder, the surface of the tool should never be allowed to fit closely against the surface of the grindstone. To pre-

vent this, tools should be constantly moved or wobbled about during the operation of grinding. (See paragraph 481)

407 (E) To lessen the danger of overheating on the emery wheel and to promote rapid grinding, tools should be dressed so as to leave the smith shop with a clearance angle of about 20 degrees, while 6 degrees only is needed for cutting. (See paragraph 474)

408 (F) Flat surfaces upon tools tend far more than curved surfaces to heat tools in grinding. (See paragraph 481)

409 (G) Tools with keen lip angles (*i.e.*, steel side slopes) are much more expensive to grind than blunt lip angles. (See paragraph 478)

410 (H) It is economical to use an automatic tool grinding machine even in a small shop. (See paragraph 486)

411 (J) There is little economy in an automatic grinder for any shop unless standard shapes have been adopted for tools, and a large supply of tools is kept always on hand in a first-class tool room so that tools of exactly the same shape can be ground in quite large batches or lots. (See paragraph 488)

412 (K) Corundum wheels made of a mixture of grit size No. 24 and size No. 30 are the most satisfactory for grinding ordinary shop tools. (See parargaph 483)

414 (L) In grinding flat surfaces skillful hand grinders invariably keep the tool wobbling about on the face of the grindstone in order to avoid heating. (See paragraph 481)

ON THE SIZE AND PROPORTION OF THE BODY OF THE TOOL

415 Twenty-five years ago it was perhaps the more general practice in this country to make the cross-section of the body of lathe and planer tools square, and this practice still generally prevails in England and upon the Continent. In fact, in the report of the Manchester experiments, referred to in paragraph 77, of this paper, in which the tools of eight of the leading engineering establishments were placed in competition, all of the tools illustrated have square shanks. Mr. James M. Gledhill also, in his admirable paper, on "The Development and Use of High Speed Tool Steel," read before the Iron and Steel Institute in 1904, refers to tools with square shanks as being the standard in use in the works of Armstrong, Whitworth & Co. It may be said, however, that the more general practice in this country at the present time is to make the depth of the body of the tool considerably greater than its width.

416 In choosing the proportion of the height of the shank to its depth, the effect of two forces must be considered—the downward

pressure upon the nose of the tool, due to cutting the chip; and the side pressure at right angles to the tool due partly to the feeding resistance, and partly to the direction in which the chip moves across the lip surface.

417 Dr. Nicolson, in his experiments, has shown that in the great majority of cases the side pressure upon the tool does not exceed 20 per cent of the downward pressure; and that more frequently the side pressure is even a smaller percentage of the vertical pressure. On the other hand, tools when properly designed and properly placed in the tool post are supported in the majority of cases almost directly beneath the cutting edge, thus directly resisting the downward pressure upon the tool, and placing it mainly under compression, and so greatly diminishing the heavy downward transverse bending and breaking strains. If, then, tools were always set in their most advantageous position in the tool post, the practice of using steel of square cross-section might not be far wrong. However, in both lathe and planer work it is often necessary to set the tool with considerable overhang beyond the tool support, and in these instances it is evident that the depth of the tool should be considerably in excess of the width; because it must be borne in mind that the transverse strength of a rectangular bar under vertical pressure increases with the square of its depth, while it increases only in direct proportion to the width.

418 It is manifestly of great importance to have the tools as light as possible consistent with their strength both for ease of handling, in setting the tool in and removing it from its tool post, in grinding and in dressing; and a much lighter tool of equal strength and stiffness can be used when the height exceeds the width than when the cross-section is square.

419 For the above reasons some of the large machine shops in this country have adopted a proportion of 2 in height to 1 in width for the cross-section of their standard tools.

420 However, owing to the desirability of turning the noses of tools high above the top surface of the body of the tool for economy in grinding and dressing, as explained in paragraphs 431 and 442 and also owing to the design of the tool posts of the greater part of the machines in this country (referred to later in paragraph 426,) it is, in the judgment of the writer, unwise to adopt a height as great as 2 to 1 for the body of the tool. After practical trial on a large scale and close observation of several different proportions, we have adopted as standard the section of 1½ in height to 1 in width for the body of the tool.

421 There is one other element, however, which requires consid-

eration, namely, the tendency to upset the tool or turn it over on to its side. It is clear that the higher the nose of the tool is raised above the point of support and the narrower the width of the tool, the greater becomes the tendency to upset the tool sideways; and that in many respects what may be called the English, Continental and old American standards of square section tools with cutting edges close to the level of the top of the tool, appear to offer far greater stability than our standard.

IMPORTANCE OF BENDING THE NOSE OF TOOLS OVER TO ONE SIDE TO AVOID DANGER OF UPSETTING

422 The tendency to upset may be mathematically defined as having the resultant line or direction of the combined vertical cutting forces and lateral feeding forces fall outside of the supporting base of the tool.

423 On Folder 2, Figs. 14, 15 and 16 we have shown three views of tools. Fig. 14 represents the English type of tool, Fig. 15 the American type, as perhaps in more common use, and Fig. 16 our standard tool. In each case the heavy line drawn from the cutting edge of the tool downward and to the left indicates the resultant line of pressure upon the nose of the tool. It will be observed that in the case of the English type of square sectioned body the resultant line of pressure falls well within the base of the tool, while in the average American type the resultant line comes close to the outer edge of the base of the tool. With our standard tool, the resultant line of pressure again falls close to the center of the base of the tool. This has been our principal reason for bending or setting the nose or cutting edge of all of our tools far over to one side of the center line of the shank, as explained in paragraph 459 and as seen in all of the views of our standard tools. Thus it will be noted that our standard toolhas all of the advantages of the American type, together with the additional stability of the English type.

424 This plan of setting the tool over to one side has also great advantages in cheapening the grinding and in diminishing the danger of overheating the cutting edge in grinding as referred to in paragraph 474.

425 The serious mistake then in the design of the average American type of body has been that of following the English and Continental practice in keeping the curve of the cutting edge symmetrical or central with the body of the tool, instead of moving it over so as to be well outside of the base of the tool.

IMPORTANCE OF LOWERING TOOL SUPPORTS IN DESIGNING MACHINE TOOLS

426 We attach so much importance to raising the nose of the tool above its top surface and at the same time having the section of the body of the tool deeper than its width, that we would especially call the attention of machine tool builders to the desirability of designing their tool supports in lathes, boring mills, etc., further below the centers than is customary. When preparing for the best shop standards in reorganizing the management of machine shops, it has become our custom to systematically go over all of the machine tools and lower the tool rests to as great an extent as is practicable. Fortunately this in many cases entails but a small expense. However, in other cases it has been found desirable and economical to re design the cross slides of many lathes so as to accomplish this object.

THE LENGTH OF THE SHANKS OF CUTTING TOOLS

427 In choosing the proper lengths for cutting tools, we again find two conflicting considerations:

428 (A) It requires a certain very considerable length for the shank of each sized tool in order to fasten or clamp it in its tool post. When the tool becomes shorter than this minimum, it must be thrown away, thus wasting costly metal, particularly in the case of the modern high speed tools.

429 (B) On the other hand, the longer the body of the tool, the more awkward and the slower become all of the operations in handling the tool, beginning with the dressing and followed by the grinding, storing, handling in the tool room, and setting and adjusting in the machine.

430 We know of no definite, clear cut method of comparing the relative loss in handling long and heavy tools with that of the waste of the tool steel, so that the adoption of standard lengths for dressing tools of various sizes has been largely a matter of "rule of thumb" judgment on our part. We give, however, on Folder 6, Table 27, the length of tools, which we have adopted corresponding to different sized bodies.

TOOLS SHOULD BE DESIGNED SO THAT LARGEST AMOUNT OF WORK CAN BE DONE FOR SMALLEST COMBINED COST OF FORGING AND GRINDING

431 In adopting the general shape or conformation of a tool (we do not here refer to the curve of the cutting edge), the most important consideration is that of selecting a shape with which the largest amount of work can be done for the smallest COMBINED COST OF FORGING OR DRESSING AND GRINDING, and the dressing is much the more expensive of these two operations. It is, therefore, of paramount importance to so design the tool that it can be ground:

a the greatest number of times with a single dressing;

b with the smallest cost each time it is ground.

432 As indicated in paragraph 201, modern high speed tools when run at economical speeds are injured much more upon the lip surface than upon the clearance flank. Therefore, at each grinding a larger amount of metal must be ground away from the lip surface than from the clearance flank; and yet in many cases the clearance flank will be more or less injured (rubbed or scraped away) below the cutting edge, and it therefore becomes necessary, for maximum economy, in practical use, to grind roughing tools both upon their lip and their clearance surfaces.

433 On Folder 3, Fig. 17e, is shown the typical wear on a tool which has been run at an economical speed. This tool has been guttered out on the lip surface and also slightly rubbed away on its clearance flank. It is evident that if it were ground on the lip surface alone a considerable amount of the metal would be wasted before the cutting edge of the tool could be completely resharpened.

434 On the other hand, it is clear that if the tool were to be ground on its clearance flank alone, a much larger amount of metal must be ground off before entirely restoring the line of the cutting edge. This shows that for economy tools must be ground both upon their lip and clearance surfaces.

335 In many shops the practice still prevails of merely cutting a piece of the proper length from a bar of steel and grinding the curve or outline of the cutting edge at the same level as the top of the tool, as shown on Folder 7, Figs. 36 and 37. This entails the minimum cost for dressing, but makes the grinding very expensive, since the lip surface must be ground down into the solid bar of steel, thus bringing the corner of the grindstone or emery wheel at once into action and keeping it continually at work. This quickly rounds over the corner of the stone, and necessitates its frequent truing up, thus increasing the cost of grinding both owing to the waste of the stone and the time

required to keep it in order; and it also leaves the face of the grindstone high in the center most of the time, and unfit for accurate work.

436 As far as possible, then, the shape of standard cutting tools should be such as to call for little or no grinding in which the corner of the emery wheel does much work. With the type of tool illustrated on Folder 7, Fig. 36, also, comparatively few grindings will make a deep depression in the body of the tool, as shown on Folder 7, Fig. 38, and this depression will of course be greater the steeper the back slope of the lip surface of the tool.

437 To avoid these difficulties, perhaps the larger number of well managed machine shops in this country have adopted a type for dressing their tools in which the front of the tool is forged slightly above the level of the tool, as shown on Folder 7, Figs. 37 and 38. This type of tool dressing is done in each of the following ways:

438 (A) By laying the tool on its side and slightly flattening its nose by striking it with a sledge, thus narrowing the nose of the tool, and at the same time raising it slightly above the level of the top of the tool, as shown on Folder 7, Fig. 38.

439 (B) By cutting off the clearance flank of the tool at a larger angle than is demanded for clearance and then slightly turning up the cutting edge of the tool through sledging upon the clearance flank while the tool is held upon the edge of the anvil with its shank below the level of the anvil. This type of dressing is shown on Folder 7, Fig. 37.

440 The objection to both of these types is that the tools require redressing after being ground a comparatively small number of times, and that when redressed in many cases the whole nose of the tool is cut off and thrown away. (This waste of metal, however, is of much less consequence than the frequency of dressing.)

441 It will also be observed that with the first of these types of tool dressing the tendency is to make the nose of the tool too thin, that is, having too small a radius of curvature, and thus to furnish a tool which must be run at too slow cutting speeds, as indicated in paragraph 326. It will be noted that both of these types of tool dressing call for at least one heating of the tool and that in most cases the tool is actually heated twice.

THE BEST METHOD OF FORGING A TOOL IS TO BEND OR TURN UP ITS END

442 Undoubtedly one of the most economical shapes for tools, when both dressing and grinding costs are considered, is that shown in our standard tools, Folder 5, Figs. 25a to 25e.

443 In examining these tools it will be noted that in the 1½ inch tool, for instance, the cutting edge is $1\frac{3}{16}$ inches above the top of the body, and if we assume that $\frac{1}{32}$ of an inch of metal ground off from the height of the tool will be sufficient to sharpen the cutting edge on an average, it is evident that a tool of this shape can be ground 24 times before the corner of the emery wheel begins to cut into the body of the tool. If after this we continue to grind the tool, there will still remain as many grindings on this tool as upon tool, Folder 7, Figs. 38 or 39b, before the wheel shall have ground down into the body of the tool for a sufficient depth to weaken it. Thus it is clear that our standard tool has a shape which permits it to be reground from three to five times as many times as the ordinary shape shown on Folder 7, Fig. 38.

444 In dressing these tools the end of the piece of steel to be made into the tool is bent or turned up by sledging it down across the corner of the anvil. Folder 1 and Folder 2 illustrate one method of doing this work. It is of interest to note that after the steel from which the tool is made has been cut to the required length and properly marked for identification, these tools up to and including tool steel of 1 inch x 1½ inch can be completely dressed by a good smith and his helper ready for grinding in two heats, providing a small steam hammer with plain flat dies is available for striking the tool a few blows at the proper time; also that without a steam hammer, each tool can be readily dressed with three heats by a smith and one helper or in two heats by a smith and two helpers, the two helpers being required for only a part of a minute.

IT IS A BAD PRACTICE TO NICK THE BAR OF TOOL STEEL AND BREAK IT OFF COLD

445 The practice of nicking the bar of tool steel with a cold chisel at points corresponding to the proper length of the tool, and then breaking it where nicked by a blow of the sledge on the anvil, is on the whole unwise, as not unfrequently almost invisible cracks are started which may only fully develop after the tool is in use. In cutting to length with a "hot chisel" a low heat is sufficient and the same heat can be used for stamping the rear end of the tool for identification.

446 The following are the steps to be taken in forging the tool after it has been cut to length from the bar.

HEATING THE TOOL

447 (A) Heat the tool rather slowly so as to insure uniform heating to the center of the bar, turning it over several times while in the blacksmith's fire. The proper heat with the modern low carbon, high tungsten and chromium steels is as high a heat as can be used without causing the steel to disintegrate or fly to pieces when struck with the sledge. Contrary to all former laws and traditions in heating tool steel, this type of steel is not injured by heating beyond a cherry red in dressing, providing the tool is finally to be heated to the high melting point according to the Taylor-White process. The proper dressing heat varies according to the chemical composition of the tool steel, but is in most cases from a yellow to a light yellow heat corresponding to a temperature of 1800 degrees F. to 1900 degrees F.

448 In the case of a tool 1 inch in the body this yellow heat should extend 5½ inches back from its point and in the following description the dimensions given will be understood to refer to a tool of this size.

449 When several tools of the same shape are to be dressed at the same time, it is best to heat them slowly in lots of, say, four to six tools at a time; the part of the tools to be heated being brought closer and closer to the hot portion of the fire as they are gradually warmed up, while the one particular tool which is to be forged next is kept directly over the hottest part. A clear coke fire, made and kept sufficiently deep to measurably prevent the blast from coming directly in contact with the tool is, on the whole, preferable to the ordinary soft coal fire used by blacksmiths. This is only true, however, because it is, on the whole, easier to get a uniform fire with coke as the fuel than when coal is used in a blacksmith's fire. The experiments described in paragraph 1010 show clearly that if sufficient care is used, a first-class soft coal fire oxidizes, and therefore injures, the tools less than a first-class coke fire.

BENDING OR TURNING UP THE NOSE OF THE TOOL

450 (B) Clamp the tool down hard on to the top of the anvil, as shown on Folder 1, Fig. 1, by drawing down the clamp *C* by means of the wedge *W*, the upper edge of which presses against the lower side of the anvil, and the lower edge against the end of the slot made

in the shank of the clamp C, which passes down through a square hole in the anvil and projects below the underside of the same. The tool is clamped so that $2\frac{3}{8}$ inches of its end project beyond the edge of the anvil.

451 (C) The blacksmith and his helper each working with a sledge bend the heated end of the tool down into the position shown on Folder 1, Fig. 2. (The exact shape of tool as thus bent over is shown on Folder 2, Fig. 7)

452 A gage similar to that shown on Folder 1, Fig. 6, should be mounted close to the blacksmith's anvil, so that he can readily test the bending of the tool to secure the proper clearance angle. This gage consists of a small surface plate with a hole drilled near one corner, into which are fitted a series of cones turned to different angles, corresponding to the various shapes into which the tools are to be bent. The tool without removing the tongs is placed with its bottom surface on the surface plate and the clearance surface against the tapered cone, where at a glance the blacksmith can see whether he has bent it to the correct angle.

453 A similar clearance gage should also be mounted close to the tool grinder so that the clearance angle called for in grinding can be quickly and accurately measured by the operator.

DRAWING DOWN THE HEEL OF THE TOOL TO SECURE GOOD BEARING

454 (D) The wedge W of clamp C is then loosened with a hammer, and the tool quickly removed to the steam hammer with flat dies, where the curved portion at the heel of the tool is placed, as shown on Folder 1, Fig. 3, upon the edge of the die, and drawn down with a few blows of the hammer so as to flatten it into a wedge shape. This flattening spreads the metal out laterally until what was a rounding corner becomes almost a right angle; thus extending the flat surface of the bottom of the tool further forward, so as to furnish a support almost under the cutting edge. (The tool in this condition is shown on Folder 2, Fig. 3)

455 In case no small steam hammer is available, the heel of the tool is flattened in a similar manner by sledging upon the blacksmith's anvil.

CUTTING OFF CORNERS OF NOSE OF TOOL SO AS TO SAVE WORK IN GRINDING

456 (E) The tool is placed upon the edge of the anvil, as shown on Folder 1, Fig. 5, and its two corners are cut off with a chisel so as to make its nose approximate to the proper curve. The bottom of the

heel of the tool is also trimmed off, if necessary, so as to make it flush with the bottom of the tool. The height is then marked with soapstone or a nick of the chisel upon the nose of the tool for cutting to the proper lip angle, and the tool is returned to the fire for its second heat.

457 It should be noted that operations B, C, D and E are all done with a single heat. If, however, at any stage in the process through lack of skill or unusual delay the tool is cooled to below a light cherry red, corresponding to a heat of 1550 degrees F., no further forging should be done without reheating.

CUTTING TO CORRECT HEIGHT AND LIP ANGLE

458 (F) After slowly and thoroughly reheating the tool, the upper portion of the nose is cut, as shown on Folder 1, Fig. 4, to the proper lip angles, care being taken to secure both the correct angle and height called for. The use of a specially designed hot chisel or set, as shown on Folder 1, Fig. 4, will help the blacksmith in this operation.

BENDING OR SETTING THE NOSE OF THE TOOL OVER TO ONE SIDE AND TRUING UP THE WHOLE TOOL

459 (G) The whole nose of the tool is then bent and set over sidewise through the use of a flatter, as shown on Folder 2, Fig. 12.

460 (H) The tool should be carefully straightened on the anvil so as to have as nearly as possible a true bearing upon its bottom surface. This bearing should extend all the way from the front to at least halfway back on the tool. A surface plate should be provided close to the blacksmith's anvil for testing the accuracy of this operation. The importance of having this bottom surface true is not ordinarily appreciated. The tool should bear at all points along its bottom surface, at its forward end, directly underneath the cutting edge, in order to avoid chatter or breaking through too much overhang; directly beneath the clamp to avoid either bending or breaking at this point.

FIRE OR HEAT CRACKS IN TOOLS COME FROM FOUR PRINCIPAL CAUSES

461 (A) Seams or internal cracks in the bar of tool steel, caused mainly by imperfections in the ingot or by too rapid or uneven heating in hammering the bar.

462 Blacksmiths are prone to attribute all cracks in their tools to the maker of the tool steel. It is our observation, however, that nine-tenths of the cracks in tools are due to bad treatment in the smith shop rather than to imperfections in the bar.

463 (B) The second cause for cracking is breaking the bar while cold, as referred to in paragraph 445.

464 (C) The third cause is heating the bar unevenly by keeping it in the same position in the fire throughout the time of heating.

465 The portion of the tool next to the fire expands more rapidly than the steel directly above it, and actually tears the colder metal apart.

466 (D) The fourth cause for cracks is too rapid heating in an intense fire. Even if properly turned over and over, the outside portions of a tool (particularly if it be of large body) are heated to a high forging heat before the center of the section has reached its proper temperature.

467 If hammered when in this condition, internal cracks in the tool are likely to be developed, because the center of the bar, instead of being malleable as the outside is, still remains comparatively cold and brittle, and the steel being unable to flow is torn apart, thus producing internal cracks. Internal cracks are also caused in some cases by hammering the outside of the bar with too light taps of the hammer. The force of the hammer blow should be powerful enough to penetrate to the center of the bar and should, therefore, increase with the size of the steel.

468 It is from the third and fourth causes (C and D) that cracks are most frequently developed and, therefore, slow heating and frequent turning of the bar in the fire are to be recommended, particularly during the early stages of heating. If the heat must be hurried, let it be during the final rise in temperature from the cherry red, say, up to the proper forging heat.

469 The above remarks refer of course to high speed tools, not to either tempered tools or the old self-hardening tools which should not be heated beyond a light cherry red in forging.

RELATIVE WORK TO BE DONE IN THE SMITH SHOP AND ON THE GRINDING MACHINE FOR MAXIMUM ECONOMY IN MAKING TOOLS

470 It requires much and careful observation, made not in a desultory manner but with a stop-watch, to determine the exact degree of accuracy with which the shape of the nose of the tool should be forged; in other words, to determine how much of the work of shaping the nose of the tool should be done by the smith and how much should be left for the grinder. It is evident that this will depend upon the method and the facilities in the machine shop for rapid and accurate grinding. If the grinding is done by hand, and on a grindstone or on a fine emery wheel, it will take a far longer time and be much

more expensive than if done on an automatic grinding machine which is supplied with a corundum wheel, the size of the grit of which is carefully selected, so as to grind with the greatest rapidity while at the same time leaving a sufficiently smooth finish. The better and more rapid the grinding facilities then, the smaller should be the percentage of work done in shaping the tool in the smith shop and the larger the percentage done by the grinder, and vice versa.

LIMIT GAGE FOR DRESSING TOOLS

471 On Folder 6, Fig. 29, is shown a gage giving the forging limits which have been demonstrated to be most economical in forging a tool of the size shown on Folder 6, Fig. 28, in shops in which first-class automatic tool grinders are used. In shops in which tools are ground by hand on an emery wheel or grindstone, it will be found economical for the smith to shape the curve of the cutting edge of the tool within much closer limits than those given in this gage.

472 This limit gage is placed with its parallel shank on top of the body of the tool, while the curved slot is directly over the curved nose of the cutting edge, hence in dressing the tool, and in approximating the curve of the cutting edge, all that is required of the smith is that every portion of the outline of the cutting edge of the tool shall come within the limits of the curved slot. On looking down through the slot in the gage, the smith should see the whole outline of the cutting edge of the tool, and provided the whole line of the cutting edge as left by the smith is in sight through this slot, it is of no consequence whether the curve is irregular and jagged in shape or whether it is left smooth. It will be cheaper for the grinder to grind off the irregularities in the curve than for the smith to take the extra time required for this purpose. Each type of tool used in the machine shop should be carefully studied in this way so as to establish the most economical limits within which the smith is to do his work, and limit gages similar to the one illustrated on Folder 6, Fig. 29, should in all cases be carefully made. The writer wishes to emphasize again the desirability of so designing tools and, particularly, of so adjusting the relative amount of work to be done by the grinder and the smith, that all sizes up to $1 \times 1\frac{1}{2}$ inch may be dressed in two heats, and still leave as little work as practicable for the grinder.

IMPORTANCE OF USING A HEAVY STREAM OF WATER DIRECTLY ON NOSE OF TOOL IN GRINDING TOOLS

473 In paragraph 1016 attention is called to the great injury which is constantly being done to the modern high speed tools by heating the cutting edge too hot on the grindstone. It becomes of the first importance in grinding, whether an automatic tool grinder is used or whether tools are ground by hand, always to throw a heavy stream of water upon the nose directly at the spot where the emery wheel or grindstone is doing its work. The practice of pouring water upon the emery wheel above the tool and allowing the stone to carry the water along with it is to be avoided, as this method provides entirely too small an amount of water to properly cool the tool. We have found by experiment that it requires a stream of water of not less than five gallons per minute, thrown directly upon the cutting edge of the tool, to prevent its being overheated on the grindstone. Even then the man running the grinder should be under frequent supervision or the temptation to force the grinding, to hurry his work and thus to overheat the tool, may prove too great. The water should be thrown in a large stream with slow velocity to avoid splashing.

474 The necessity for not overheating the tool in grinding also modifies the shape for forging our standard tool. It will be noted that the noses of our standard tools as they come from the smith shop, shown Folder 2, Figs. 11 and 12, have clearance angles of 20 degrees, whereas a clearance angle of 6 degrees is ample for shop use. In other words, the noses of our standard tools lean far forward out of the perpendicular. The object of this is to make the distance beneath the cutting edge, which must be ground off of the flank each time the tool is sharpened as short as possible. In this way a smaller pressure between the tool and the grindstone is called for, the tool is ground in a much shorter time, less heat is generated by the grindstone, and there is less danger of injuring the tool from overheating.

475 By noting also tool shown on Folder 2, Figs. 10 and 11, it will be seen that the nose when cut off by the blacksmith has a much more acute lip angle than is actually needed in the machine shop for cutting. This acute angle is given the tool for the same reason as was the extra clearance angle, namely, to diminish the extent of the surface which must be ground from the lip surface of the tool. The diminution in the grinding which results from leaning the nose of the tool forward and cutting a much steeper side slope in the smith shop becomes apparent from a comparison of Folder 2, Fig. 11, with the view of a tool dressed and ground in the ordinary way, as shown on Folder 7, Figs. 36, 37 and 38.

476 In drawings shown Folder 5, Figs. 25a to 25e, it will be noted in each case that broken lines above and beyond the upper part of the nose of the tool indicate the shape to which the tool is forged, while the solid, heavy lines indicate the shape to which the tool is ground at its first grinding.

477 Our reason for leaving so much metal in the forged tool to be ground off is that sometimes in giving the tool the high heat, owing to too slow a fire being used, the metal close to the surface of the nose of the tool is somewhat injured, and by grinding off this exposed point of the tool at its first grinding, a tool which runs at once at its highest cutting speed can be obtained.

TOOLS WITH KEEN LIP ANGLES (I. E., STEEP SIDE SLOPE) MUCH MORE EXPENSIVE TO GRIND THAN THOSE WITH BLUNT LIP ANGLES

478 While on the subject of grinding, it should be pointed out that the steeper the side slope of the lip surface, the larger becomes the area of the surface which must be ground and the smaller the number of times a tool of a given height can be ground before redressing. This will be clearly seen by inspecting Folder 5, Figs. 23, 20a and 20b; in one of which successive layers of $\frac{1}{32}$ of an inch of metal are to be ground off with a side slope of 14 degrees or at right angles to the vertical line, while in the other a side slope of 22 degrees is used in grinding.

479 A steep side slope also renders the cutting edge more likely to be overheated in grinding as it leaves a smaller cross-section of metal in the wedge-shaped section close to the cutting edge for carrying away the heat, as pointed out in paragraph 516.

480 If economy of grinding alone then were to be considered, a steep side slope in the tool would be avoided for every reason. A consideration of the above facts will also make it more clear why all machinists who grind their own tools incline toward too little rather than too much side slope.

FLAT SURFACES TEND TO HEAT THE TOOLS IN GRINDING

481 Flat surfaces coming into contact with the emery wheel also tend very greatly to heat the tool, chiefly because the surface which is being worked upon is soon ground so as to fit so exactly and closely against the outside surface of the grindstone that no water can find its way between the stone and the tool and thus cool the latter. It is for the purpose of giving the water free access to the face of the tool being ground that in grinding tools by hand the best grinders invariably keep the tool more or less wobbling about upon the face

of the grindstone while the greater part of the metal is being roughed off. For the same reason they hold the tool stationary against the stone only during the last stage of the grinding when finishing the lip surface to the exact angle required. In selecting an automatic grinder, no machine should be purchased which does not permit free access of the water to the flat surface of the tool during the operation of grinding.

482 It is for a similar reason also that tools with a curved cutting edge are to be preferred from the standpoint of grinding to those with a straight line on the cutting edge. The straight line always implies a flat clearance surface beneath the cutting edge for grinding, and a flat surface is far more difficult to grind without heating than a curved surface.

THE SELECTION OF THE EMERY WHEEL

483 The selection of the proper emery wheel for tool grinding is also a matter of great importance. The hardest grit obtainable should be used, and for grinding ordinary shop tools, so far as we know, corundum is the best. Rapid grinding is promoted by the use of a coarse grit in the wheel. On the other hand, too coarse grit leaves an irregular outline at the cutting edge of the tool. After experimenting with emery wheels varying greatly in their coarseness, we have adopted as our standard an emery wheel having a mixture of grits known as size No. 24 and size No. 30. A corundum wheel made of these two sizes of grit grinds fast and leaves a sufficiently smooth finish on the tool.

DESIRABLE FEATURES IN AN AUTOMATIC TOOL GRINDING MACHINE

484 Tools should never be ground by fastening them solidly in a slide or tool rest which is fed directly against the emery wheel with a screw; since soon after the grinding starts, the surface of the tool is made to fit exactly against the surface of the stone, after which grinding is exceedingly slow and the tool is rapidly overheated. It may almost be said that the moment a tool becomes a close fit against the side of the grindstone, grinding ceases and heating begins.

485 Much more rapid grinding can be done upon a grinding machine in which there is provided a means for automatically adjusting the pressure of the tool against the emery wheel. Each sized tool should have adapted to it a pressure which is automatic and which is just sufficient to grind rapidly without danger of overheating. An automatic machine of this type will do about twice the work of a ma-

chine in which the pressure between the tool and the emery wheel is regulated according to the judgment of the grinder.

DESIRABILITY OF A LARGE SUPPLY OF TOOLS, A COMPLETE TOOL ROOM, AND AN AUTOMATIC GRINDING MACHINE EVEN IN A SMALL SHOP

486 In pars. 115 etc. we have pointed out that the greatest gain from a study of the art of cutting metals can be attained only through reorganizing the system of management of the shop in such a way that it is possible to assign daily tasks to the workmen, and that in preparing for this a thorough system must be established for delivering to each workman an ample supply of tools ground to standard shapes ready for use. This involves a tool room with ample storage space for a large number of extra tools. For economy, even in a small shop, the tools should be ground in lots or batches; *i. e.*, there should be such an ample supply of tools in the shop that dull tools of a given size and shape can be allowed to accumulate until a lot, say, ten to twenty or more, is ready for the grinder. With this system it is economical for the small shop as well as the large one to use an automatic tool grinder.

487 In our experience in reorganizing the management of machine shops we almost invariably have difficulty in persuading the owners to maintain the large supply of tools which is needed to get the full benefit from the task system. It seems desirable, therefore, to lay particular stress upon all of the elements connected with the tool supply—of which accurate and rapid grinding without injuring the tool is the most important.

488 We would call attention to the fact that there is little if any economy in the use of an automatic tool grinding machine unless standard shapes for all tools have been adopted, and unless a large supply of tools is kept in a well-equipped tool room, from which they are issued to the men, no workman being allowed to grind his own tools.

PRESSURE OF THE CHIP ON THE TOOL

489 In the following paragraphs 490 to 585 the subject of the pressure of the chip upon the tool will be dealt with at length, even although in most of its aspects an investigation leads to negative or more or less contradictory results. Indeed, our principal object in writing at such length upon this subject has been to endeavor to make it clear that, on the whole, a study of this element in the art of cutting metals is comparatively barren of practical results. It is our hope, therefore, that we may convince our readers that a study of the

pressure of the chip on the tool leads to few useful conclusions so far as the vital question of cutting speeds is concerned.

490 As indicated in paragraphs 73, 75 and 92, this element has been the subject throughout the world of perhaps four-fifths of all the experiments connected with the art. And yet we believe that our contention that greater progress would have been made if no experiments whatever had been undertaken in this particular field is thoroughly borne out. The chaotic results obtained through these pressure experiments have unquestionably held back further scientific research in the whole art, and led experimenters to the conclusion that after all this subject belongs to the domain of "rule of thumb" rather than to that of exact science. If, therefore, the writing of this paper shall result in diverting the attention of future experimenters from this field to the many more useful lines of investigation, we feel that one of our chief aims will have been realized.

SUMMARY OF CONCLUSIONS OF ENGLISH, GERMAN AND AMERICAN EXPERIMENTERS

491 On Folder 12, Table 83, are given the broad conclusions arrived at by experimenters in Germany, England, and this country, respectively, as to the pressure of the chip upon the tool in cutting steel and cast iron. The figures from the German experiments are taken from an article by Herman Fischer (published in "Zeitschrift des Vereines Deutscher Ingenieure" of May 1, 1897), who, after reviewing various German experiments made from time to time and considering their reliability, states that, according to the hardness of the material, the shape of the cutting edge of the tool, including the clearance and lip angles and its dullness within permissible limits, and the relation between the length and thickness of the chip which is being cut, the pressure per square inch of section of the chip varies between the limits given in the table. He also recommends that in designing machine tools, the higher figures for the cutting pressures be counted upon.

492 Dr. Nicolson in summarizing the Manchester experiments and his own experiments made later with his highly perfected apparatus, has concluded that the pressure on the tool is directly proportional to the sectional area of the cut, that is, of the layer of metal being removed by the tool. He concludes that the pressure for the same total area is the same whether the thickness of the chip be fine or coarse. This is not in agreement either with the German experiments or our own, as the latter show increasing pressures as the thickness of the chip

diminishes, particularly in the case of cutting cast iron. (See paragraphs 546 to 558)

493 It must be noted, however, that in the Manchester experiments $\frac{1}{16}$ of an inch was the finest feed taken whereas our experiments indicate a greater proportional increase in pressure as the feeds become finer than $\frac{1}{16}$ of an inch. Our experiments indicate that the pressures vary between the limits given on Folder 12, Table 83. In the case of steel they slightly increase as the thickness of the shaving diminishes; and in the case of cast iron very materially increase as the thickness of the shaving diminishes.

494 As to the effect of cutting speed upon the pressure of the chip, the conclusions from the Manchester experiments and from our own are that there is but slight difference in pressure between fast and slow cutting speeds, but that the total power required to remove a given amount of metal is less at fast than at slow cutting speeds, owing chiefly to the diminution in the frictional resistance of the machine tool and its drive at higher speeds.

495 Dr. Nicolson's experiments indicate that the outward or "surfacing" pressure upon tools or the pressure tending to push the tool away at right angles to the axis of the work varies according to the contour of the cutting edge and the lip and clearance angles of such tools as are in common use between the limits of 18 per cent and 90 per cent of the vertical pressure upon the tool, while the feed or "traversing" pressure upon similar tools vary between zero and 20 per cent of the vertical pressure.

496 In measuring the outward and feeding pressures Dr. Nicolson has designed much the most scientific apparatus which has yet been made. Nevertheless, engineers must be warned not to use the feeding pressure obtained by him in designing machine tools, as both the German and our own experiments indicate that at times the feeding pressure is equal to the entire downward pressure on the tool. Doubtless Dr. Nicolson would have arrived at the same conclusion had he made more experiments, and particularly with tools which are too dull for proper shop use. This degree of dullness, however, will occur on every machine tool sooner or later, and the pressure corresponding to it must, therefore, be the limiting figure used in designing feed gearing, as otherwise the feed gears will be broken.

497 In paragraph 97, (Part 1) of this paper, the writer has made the assertion that it is his opinion that if no experiments whatever had been made upon the pressure required to remove the chip, the knowledge of the art of cutting metals would on the whole be in a more advanced state than it is now, since experimenters in all countries in

this field, instead of almost wholly wasting their time in pressure determinations would have given their attention to some one of the other lines of investigation which bear directly and yield valuable information upon the one most important subject of cutting speed.

498 Before entering upon the details of our experiments upon the cutting pressure, it seems desirable to explain briefly, first, the facts upon which the above assertion rests, and, second, if possible to give an adequate explanation for these facts.

499 In 1883 in the works of Wm. Sellers & Co., of Philadelphia, a series of experiments was made by Messrs. Wilfred Lewis and John Bancroft with a dynamometer, in which the pressure of the chip upon the lip surface of the tool was measured. These experiments showed that for steels varying greatly in hardness and consequently in their cutting speeds, the variation in the pressure of the chip upon the tool in no way corresponded either to the hardness of the steel or to the speed at which it could be cut. A further study of the results of these experiments indicated also that there was no clearly defined and traceable relation between the tensile strength or the crushing strength of steel and the cutting speed. These results agreed accurately with the observations,which we had made in our many experiments on cutting speeds. Namely, that lathes, boring mills, etc., are able to pull about as heavy cuts with hard as with the soft steels, although there is a very great difference between the cutting speeds of hard and soft steels. Having established this important fact to our satisfaction and having through these experiments obtained sufficient data for properly designing machine tools as to the power required to cut metals, no further experiments were made by us in this line until the year 1902, when the subject was again more carefully investigated through dynamometer experiments in the shop of Wm. Sellers & Co. These experiments will be described later in this paper.

500 In the Manchester experiments (described in paragraphs 77 to 92) the pressures of the chip upon the tool were carefully recorded and averaged, and the metals experimented upon were chemically analyzed and test bars broken to determine their physical properties. A summary of these experiments in cutting steel forgings, as they bear upon the relation of cutting speed to pressure on the tool and to the tensile and crushing strength of the metals being cut, has been tabulated on Folder 12, Fig. 81, together with our own experiments on the same subject, and on Folder 12, Fig. 80, are tabulated corresponding experiments made in cutting cast iron bars of varying hardness.

501 In the five columns, side by side, will be noted in heavy-faced

type the more important elements which should be studied in their relations one to another, namely:

a The cutting speed in feet per minute;
b pressure of chip on the tool in tons (2000 lbs.) per square inch of sectional area of the shaving;
c tensile strength in tons (2000 lbs.) per square inch;
d percentage of stretch in test bars;
e crushing strength in tons (2000 lbs.) per square inch.

CUTTING SPEED AND PRESSURES OF CHIP ON THE TOOL COMPARED FOR STEEL

502 Referring to Folder 12, Table 81, on "Pressure on Tool in Cutting Steel Forgings and Castings," it is a matter of common knowledge that as the percentages of carbon and manganese increase in steel, the metal grows harder, and that corresponding to this increase of hardness, the cutting speed grows slower and slower. By looking in the carbon column and then in the cutting speed column of the table, the slowing down in the cutting speed corresponding in a general way to the increase in carbon will be apparent. On the other hand, when we compare the tensile strength in tons (2000 lbs.) with the cutting speed, we should expect here also to find that as the tensile strength of the steel increases, the cutting speed diminishes. This is, however, not the case, and a very marked and at first unaccountable irregularity exist between the tensile strength and the cutting speed. Although it may be said that in a very general way steels having higher tensile strength tend toward lower cutting speeds.

503 When we examine, however, the more important subject of the relation of the pressure on the tool to the cutting speed, it is astonishing to note that there is no traceable relation whatever between the two. For example, referring to line 1 of the table a pressure of 128 tons upon the tool is accompanied by a cutting speed of 111 feet per minute, while on line 5 a pressure of 128 tons has a cutting speed of only 35 feet per minute, while again on line 2, 121 tons pressure on the tool has only 80 feet cutting speed. To a considerable extent also, there is the same lack of agreement between the tensile strength of the steel and the pressure of the chip on the tool. For example, on line 3 a tensile strength of 52 tons is accompanied by a pressure on the tool of 168 tons while on line 7 a tensile strength of 48 tons has a pressure of only 92 tons.

504 These statistics leave the student of this subject in a most chaotic state of mind, and of the many anomalies and surprises met

with by experimenters in the art of cutting metals, the most baffling and apparently unaccountable are the following facts:

505 No law can be established or formulated for cutting steel which expresses either

a the relation between cutting speed and the pressure on the tool; or

b the relation between cutting speed and the tensile and crushing strength of the metal to be cut.

THEORY AS TO WHY NO ACCURATE RELATIONS EXIST BETWEEN PRESSURE ON TOOL AND CUTTING SPEED, TENSILE STRENGTH, ETC.

506 Generally speaking, theories must be accepted with less confidence than facts. The writer, however, ventures to offer the following theory in explanation of the above phenomena as at least corresponding closely to the facts.

507 It will be recalled that although the tensile strength of soft steels is much lower than that of hard steels, yet in many cases it requires more foot pounds of energy to break by pulling apart in a testing machine a test bar of low tensile strength than one of high tensile strength. The reason for this is that the percentage of stretch or extension in the soft steel bar is in most cases much greater than that in the hard steel. (See tensile strength, stretch, and carbon columns of Folder 12, Table 81) When we consider the fact that throughout the time that a test bar is stretching, all of the grains inside of the bar are continually flowing, moving or sliding past one another under what may be called very heavy internal friction, it becomes clear that in spite of the fact that the pull or power required to cause flow in the grains or crystals of the soft steel is less than the pull required to move the grains of a hard steel bar, yet the greater distance through which the grains of the soft steel continue to flow more than makes up for the difference of tensile strength in the final sum total of energy expended.

508 In paragraphs 155 to 169 the writer has indicated the fact that in tearing a chip from a bar of steel, the grains or molecules of the metal of the chip are caused to flow past one another under very severe compression for a considerable distance, so that the thickness of the layer of metal being removed is double in the chip what it was originally on the forging. In the case of a chip torn from soft metal, the movement or flow of the grains of the chip past one another is much greater than in the case of a hard chip. In other words, a soft steel chip is thickened up in cutting much more than a hard steel chip.

509 Thus it becomes clear why in cutting a chip the total energy expended and the pressure of the chip on the tool are in many cases greater with a soft steel than with a hard steel.

510 Attention is called to the fact that in cutting soft steel, owing to the fact that it thickens more than the hard steel, the chip bears upon the lip surface of the tool over a much larger area than in cutting hard steel, and although undoubtedly the intensity of the pressure on any one small spot on the lip surface of the tool is greater in cutting hard steel than in cutting soft steel, yet the larger area which is under pressure with the soft steel chip more than makes up in many cases for the difference in the intensity. Therefore, frequently a heavier total pressure is produced with the soft steel than with the hard. It should be noted, however, that in breaking a tensile test bar, the molecules or grains of metal in most cases continue to flow or move past one another until the entire metal of the bar has reached close to its maximum possibility of flow, and until it is at all points ready for rupture, almost all of its potential flowing energy having been exhausted. But in the case of the pressure of the tool upon the chip, the conditions are evidently such that the tool cannot completely use up all of the potential energy in the metal which is being cut, so that doubtless each of the small elements into which the chip breaks up could be crushed and the grains caused to flow past one another still further before entirely reaching the collapsing point. In other words, breaking a tensile test bar is a more efficient means of using up the potential flowing energy of steel than is the crushing action of the tool in removing the chip. If the two methods were equal in using up flowing energy, then we should expect to find the pressure on the tool directly proportional to the tensile or crushing strength of the steel multiplied by its percentage of stretch. This is not, however, accurately the case, and, generally speaking, the harder the steel being cut, the larger the proportion of potential flowing energy that will be used up by the tool in cutting the chip, so that of the two elements or properties of steel which tend to increase the pressure of the chip on the tool—*i. e.*, the tensile strength of the metal and its percentage of stretch—the tensile strength counts for most in producing pressure on the chip. (See paragraphs 572 to 575)

511 The pressure of the chip on the tool is doubtless greater, the finer the quality of the metal which is being cut, *i. e.*, in metals which combine both a high tensile strength and a comparatively large percentage of stretch; such, for instance, as the fine qualities of low phosphorous steels which have been most carefully worked in forging, or the thoroughly oil tempered and annealed gun forgings, or high

grades of tool steel, in all of which exceedingly high combinations of tensile strength and stretch are attained. And again it should be noted that although the pressures on the tool are high in these fine qualities of steel, yet the cutting speeds are by no means proportionally slow. The slowest speeds are to be found in cutting chilled iron or more or less hardened steels, which generally have an exceedingly low percentage of stretch and also comparatively low pressures on the tool.

512 An illustration of this will be seen by referring to Folder 12, Table 81, which furnishes the comparison given below of three pieces of metal. In the first line will be found a forging consisting of a good quality of hard steel experimented upon in the Manchester experiments, and in the second and third lines a steel roll and a car wheel casting necessarily inferior in quality to a forging experimented upon by Wm. Sellers & Co., of Philadelphia. Both of the steels tested by Sellers are evidently inferior to the Manchester steel.

The details of these three experiments are as follows:

KIND OF METAL	CARBON PER CENT	TENSILE STRENGTH IN TONS (2000 LBS.)	PERCENTAGE OF STRETCH	PRESSURE OF CHIP ON TOOL IN TONS (2000 LBS.)	CUTTING SPEED IN FEET PER MINUTE
Steel forging	0.50	52	14	168	41
Steel roll	0.55	51	8	128	35
Steel car wheel casting	0.82	48	3	92	22

513 It will be noted that the percentage of carbon of this forging and roll are about the same, and that the tensile strengths of all three are also about the same. On the other hand, the stretch of the roll is only a little more than one-half that of the forging, showing an inferior quality of metal. The casting has a still lower stretch and is of still lower quality, because it has not received work under the hammer. And this falling off in the quality of the metal indicated by low stretch is also accompanied by a falling off in the pressure of the chip upon the tool; the casting having only 92 tons, the roll having only 128 tons pressure, while the forging has 168 tons. Thus we see that an inferior quality of metal is accom-

panied by a lower pressure upon the tool. If the metal in the casting had been forged, its tensile strength would probably have not greatly increased, but it would without doubt have had a very materially higher percentage of stretch, and the pressure on the tool would have increased accordingly.

514 It will be noted that the car wheel casting, which gives a pressure on the tool of only 92 tons per square inch sectional area of the shaving, has a slower cutting speed than any of the other samples of steel which were cut, and yet it has the lowest total pressure on the tool of any steel. This is an excellent illustration of the fact that the hardness in steel which causes a low cutting speed is not accompanied by the highest pressures on the tool. On the other hand, this steel casting has only 3 per cent of stretch and it is undoubtedly this low percentage of stretch which accounts for the slow cutting speed. We shall attempt to fully explain this point later in the paper.

515 It is undoubtedly true that the heat which is caused by the pressure of the chip upon the surface of the tool is, broadly speaking, directly proportional

a to the pressure of the chip upon the tool;

b to the cutting speed (*i. e.*, the velocity with which the chip slides across the lip surface);

c to the coefficient of friction between the chip and the tool, which is dependent upon the roughness of the lip surface and undoubtedly grows greater as the surface becomes softer.

516 On Folder 8, Figs. 43 and 44, on an enlarged scale are shown the noses of two tools, one cutting a chip of hard steel and the other one of soft steel. The layer of metal being removed from the forging is in both cases of the same thickness. However, it will be noted that the soft steel chip where it presses upon the tool has become very much thicker than the hard steel chip, and also that it bears upon almost twice the area of the lip surface of the tool as does the hard chip. In each view the arrow indicates the center of pressure of the chip upon the lip surface of the tool; and it should be observed that the softer the steel, *i. e.*, the greater its per cent of stretch, the further is the center of pressure of the chip removed from the cutting edge. Now, as explained hereafter, the heat produced by the friction of the chip must be carried away principally down through the nose to the body of the tool. In each view the line $A-B$ represents the section of the tool opposite the center of pressure of the chip which is available for starting the heat on its way downward. It will be noted that

the section $A—B$ in the case of the hard chip is much smaller than it is in the case of the soft chip, while at the same time it is much closer to the cutting edge of the tool. Thus, even assuming that the total heat produced by the soft steel chip is greater than that produced by the hard steel chip, nevertheless, on the one hand, there is much more metal available in the case of the soft steel chip for carrying the heat away; and on the other hand, the center of heat, $A—B$, is further away from the cutting edge, which is that portion of the tool which finally gives out. In addition to this, owing in the case of cutting the hard metal to the small bearing of the chip on the lip surface, the pressure is doubtless much more intense (*i. e.*, greater per square inch of the lip surface under pressure), and therefore in this case the lip surface of the tool must remain much harder in order to resist wear.

517 It will be observed then that all of these conditions combine to necessitate a slower cutting speed for hard metals than for soft, even if the total pressures of the chip on the tool were to be exactly the same for hard and soft metals. To summarize:

a In cutting hard metals the intensity of the pressure per square inch of the lip surface of the tool which comes in contact with the shaving is much greater than in cutting soft metals;

b the center of pressure is much closer to the cutting edge;

c the section of metal directly below the center of pressure is smaller for carrying the heat away.

518 All of these conditions which tend greatly toward lowering the cutting speed are brought about not so much through the greater crushing strength of hard steels as through the smaller percentage of stretch in hard steels (*i. e.*, a smaller capacity for flow).

519 In paragraphs 1129 to 1165, relating to the classification of various metals according to their hardness, it will be pointed out that extending over quite a considerable range in hardness, a well defined law appears to exist, and a formula has been developed in which the cutting speed of steels is shown to bear a clearly defined relation to certain combinations of tensile strength and percentage of stretch.

CUTTING SPEED AND PRESSURE OF CHIP ON THE TOOL COMPARED FOR CAST IRON

520 Referring now to Folder 12, Table 80, on the "Pressure of the Chip on the Tool in Cutting Cast Iron," by examining the columns for cutting speed and the pressure of the chip in tons (2000 lbs.) it will be noted that there is also here no direct relation between the

cutting speed and the pressure on the tool. For instance, a pressure of 94 tons per square inch of sectional area of the chip of medium cast iron is accompanied by a cutting speed of 49 feet per minute, while a pressure of only 92 tons is accompanied by a speed of 32 feet per minute; yet, as explained in pars. 93 and 503, one would naturally expect higher pressures on the tool to be accompanied by slower cutting speeds.

CUTTING SPEED AND CRUSHING STRENGTH COMPARED FOR CAST IRON

521 In comparing the crushing strength with the pressure on the tool, the two seem to be more nearly in inverse proportion one to the other in the case of cutting cast iron than in the case of cutting steel, and yet we have the two combinations of

a 49 tons crushing strength with 49 feet cutting speed; and

b 47 tons crushing strength with 32 feet cutting speed, showing that there is no constant relation between the two.

CAST IRON AND STEEL COMPARED IN THE RELATION OF CUTTING SPEED TO PRESSURE ON TOOL

522 In comparing cast iron and steel in the relation of pressure of the chip on the tool to the cutting speed, it is surprising to note that:

523 Generally speaking, the cutting speeds of cast iron are slower than the cutting speeds of steel, while at the same time the pressure of the chip on the tool in cast iron is much less than the pressure on the tool in cutting steel. The theory which we have advanced, however, in paragraphs 506 to 519, appears to account for this difference. It is well known that there is almost no stretch in breaking a cast iron test piece, nor does a compression bar yield to any great extent before the cast iron entirely crumbles. This lack of stretch, as explained, indicates the inability of the grains of cast iron to flow past one another under pressure; and since the metal has no ability to flow, the whole pressure of the chip is concentrated on the lip surface of the tool very close to the cutting edge, so that per unit of area of the lip surface in contact with the cast iron shaving the intensity of pressure is probably as great as in that of the steel chip. It is also probable that cast iron containing more carbon in the form of gritty graphite which is combined in a very hard state, is more abrasive in its action on the tool. All of these conditions tend toward rapid wear of the tool close to the cutting edge, and, therefore, also toward slow cutting speeds.

524 It is notable that the whole tool is heated to a much lower

heat in cutting cast iron than in cutting steel, and yet the tools give out at slower cutting speeds.

APPARATUS USED AND METHOD OF MAKING EXPERIMENTS ON THE PRESSURE OF CHIP ON THE TOOL IN CUTTING CAST IRON AND STEEL

525 Two series of experiments for determining the pressure of the chip on the tool in cutting steel and cast iron have been made by us. One set made in 1884, in the Midvale Steel Works, Nicetown, Philadelphia, is of interest only in relation to the power required to feed the tool. The second set was made with greater care and with better appliances in 1902 in the shop of Wm. Sellers & Co., Philadelphia. The latter experiments only will be described in detail.

526 With the object of warning any future experimenters against the adoption of certain methods in this field, it seems desirable to briefly describe one method which after trial proved to be unreliable and was abandoned by us.

527 A lathe swinging 16-inch diameter over the shears and 13½ inch diameter over the saddle was driven by a 20 horse power motor using a current of 220 volts; with a belt running directly from the pulley on the motor to the cone pulleys on the lathe. These cone pulleys drove with the following gearing intervening between them and the face plate of the lathe. Pinion on sleeve of cone pulley: 15 teeth, 3 per inch, 5-inch pitch diameter, 4½ inch face. Wheel on spindle: 120 teeth, 3 per inch, 4-inch pitch diameter, 4-inch face.

528 Many trials were made to determine the pressure of the chip on the tool by first reading the ammeter while the motor was running without the cut, and then noting the difference in its reading after the tool was cutting, and assuming that the difference in the power used in the two cases was equal to the work done by the tool.

529 This method proved unsatisfactory as the fluctuations of the needle of the ammeter were so great under light loads that it was found impracticable to judge with accuracy its average reading. Therefore, as an error in estimating the ampères of current not only directly affects the electrical power expended, but even still more affects the determination of the efficiency of the motor when running under light loads, this method was abandoned as unreliable.

530 An endeavor was then made to work the motor constantly under a heavier load by attaching an accumulator pump to it in addition to running the experimental lathe. This, however, also proved unsatisfactory, owing to fluctuation in the power of the pump.

APPARATUS USED IN EXPERIMENTS ON PRESSURE OF CHIP ON THE TOOL

531 The following simple device was then adopted, with which accurate results were obtained, and which were repeatedly re-duplicated, thus proving at least the uniformity of the whole method.

532 A rope brake was used on one of the steps of the cone pulley of the lathe. This brake, illustrated on Folder 9, Fig. 51, was at that time a somewhat recent improvement on a Prony brake, and consisted merely of a double rope slung around the pulley, having each of its ends attached to spring balances, one of which is stationary and the other of which is attached to the end of a draw screw, which is tightened or loosened by means of a hand wheel whose hub is used as a nut for the screw. The method of experimenting with this apparatus is as follows:

533 After the tool has been run for a sufficient length of time under cut to bring both the tool and the lathe to what may be called natural conditions as to wear, heat, friction, etc., the reading of the ammeter is noted as accurately as possible while the tool is under pressure. The tool is then removed and the brake is adjusted upon one of the steps of the cone pulley, and tightened until the ammeter reads the same as it did when the tool was under cut. At the same time the readings of the two spring balances are taken; and, since the difference in the readings of the two balances is the effective pull caused by the friction of the brake reduced to the central diameter of the brake rope, by multiplying this pull by the central diameter of the rope and by the ratio of reduction from the cone pulley to the lathe spindle, and then dividing this product by the mean diameter of the forging upon which the cut was taken, the quotient obtained gives the pressure on the tool. In this way all of the power lost through friction throughout the entire apparatus is eliminated with the exception of the small difference in the frictional resistance of the bearings and gears which lie between the brake and the tool. It will be observed that the difference in the friction of these parts is small between the two cases when, on the one hand, the tool is cutting, and, on the other hand, the brake is tightened. This difference (unmeasured when the brake is on) must be proportional to the pressure on the tool and, therefore, will in no way affect the relative pressures of the different cuts.

534 It should be noted that it is necessary to take the reading of the ammeter and the two spring balances as soon as practicable after the brake is applied, and before the cone pulleys and ropes become so heated as to cause variation in the frictional resistance of the brake. When this is done, the method is both delicate and accurate.

DETAILS OF EXPERIMENTS UPON THE PRESSURE OF THE CHIP ON THE TOOL IN CUTTING CAST IRON WITH OUR STANDARD TOOLS WITH VARIOUS FEEDS AND DEPTHS OF CUT

535 The following are the general conclusions arrived at on this subject:

536 (A) Total pressure of chip on tool in cutting cast iron of the different qualities experimented upon by us varies between the low limit of 35 tons (2000 lbs.) per square inch sectional area of chip for soft cast iron, when a coarse feed is used, see Folder 12, Table 83, and Folder 13, Table 92, and 99 tons (2000 lbs.) per square inch sectional area of chip for hard cast iron, when a fine feed is used. (See Folder 13, Table 92; also paragraphs 544, etc., and 491)

537 (B) In cutting the same piece of cast iron, the pressure of chip on the tool per square inch sectional area of chip grows considerably greater as the chip becomes thinner, and slightly greater as the cut becomes more shallow in depth. The following are the high and low limits of pressure per square inch of sectional area of the chip when light and heavy cuts are taken on the same piece of cast iron. (See Folder 13, Table 92, column for $1\frac{1}{4}$ inch tool)

Depth of cut $\frac{1}{4}$ inch $\times$ feed 0.0328 inch : Total pressure per sq. in. sectional area of chip, 128,000 lbs.;

Depth of cut $\frac{1}{16}\frac{1}{4}$ inch $\times$ feed 0.1292 inch : Total pressure per sq. in. sectional area of chip, 75,000 lbs.

538 (C) The same fact mathematically expressed is that in cutting the same piece of cast iron, the pressure of chip on the tool per square inch sectional area of chip grows greater as the thickness of the chip grows less in proportion to (thickness of the feed)$^{\frac{1}{2}}$ or $F^{\frac{1}{2}}$. (See paragraph 546)

539 The pressure of chip per square inch of section also grows greater as the depth of the cut grows less in proportion to (depth cut)$^{\frac{1}{10}}$ or $D^{\frac{1}{10}}$. (See paragraph 546)

540 (D) The effect upon the pressure of the chip on the tool of a change in the thickness of the feed and the depth of the cut is the same for hard and soft cast iron, and is represented by the same general formula, with a change merely of the constant. (For formula, see paragraph 546, and for description of experiment on which this fact is based, see paragraph 562)

541 (E) In taking cuts having the same depth and the same feed, the pressure of the chip on the tool becomes slightly greater the larger the cutting tool that is used. This increase in the pressure

follows from the fact that the larger the curve of the cutting edge of the tool the thinner the shaving becomes. (See paragraphs 307 and 559)

OBJECTS OF EXPERIMENTS ON PRESSURE

542 The principal object in making the experiments described in detail below was to determine, broadly speaking, the maximum pressures upon the tool per square inch of sectional area of the chip, both in cutting soft and hard cast iron, when our standard shop tools of different sizes were used; this information being needed in designing machine tools, for this purpose the highest pressure of 99 tons (2000 lbs.) as indicated on Folder 13, Table 92, should be sufficient.

543 Our secondary object, and one of almost equal importance, was that of obtaining the pressure on the tool per square inch of sectional area of the chip being cut, corresponding to various changes in the depth of cut and in the thickness of the feed. This information is needed in determining by means of our slide rules, described in paragraph 1188 the exact sized cut which each machine tool is capable of taking under its possible combinations of pulling power, speed and changes in the thickness of feed.

544 On Folder 13, Table 92, will be seen a summary of the actual pressures obtained under various conditions in these experiments, and in adjoining columns the pressures are reduced to pounds per square inch of sectional area of chip. The same data are recorded in the diagrams, Folder 13, Figs. 87 to 91, by means of round spots which are connected in series one with another by faint lines, so that all of the experiments made with the same depth of cut can be readily compared.

545 On the left-hand side of each of these diagrams are recorded the regularly increasing pressures per square inch of sectional area of the chip upon the tool; while on the bottom line are recorded the regular increases in the thickness of the feed.

546 In a series of heavy lines on each diagram are drawn curves corresponding to the following formula, which expresses the general relation existing between the depth of cut and the feed, and the pressure on the tool for all of the grades of cast iron experimented upon:

$$P = C\, D^{\frac{11}{16}}\, F^{\frac{1}{2}}$$

in which

P = The pressure on the tool;
D = Depth of cut in inches;
F = Feed in inches;
C = A constant depending upon the softness or hardness of the cast iron, and which varies between the limits of 45,000 for soft and 69,000 for hard cast iron, as experimented on by us.

547 On Folder 13, Fig. 87, are combined all of the various experiments given in detail in the other diagrams. In these diagrams the heavy lines represent the same formula above referred to, while the round spots which are grouped together in series indicate all of the pressures obtained with the various sized tools used and with the different feeds and depths of cut taken in the several sets of experiments.

548 It will be noted that, on the whole, the law expressed by this formula corresponds very closely to each of the several series of experiments. These experiments were made on different dates, and the pressures were accurately recorded without reference in any case to the data obtained in former experiments. And the fact that they all, on the whole, so closely conform to the same general law, tends greatly toward confirming both the value of the apparatus and of the method employed, and also the accuracy and care of the experimenters.

549 It will be remembered, as stated above, that the conclusion drawn from the Manchester experiments was that the pressure of the chip upon the tool per square inch of sectional area of chip was directly proportional to the area of the chip and was the same whether light or heavy cuts were taken, and that it did not depend upon either the thickness of the feed or the depth of the cut. This conclusion is at variance with our experiments and with the formula in paragraph 546, which mathematically expresses our results. It may be claimed that the slight difference in the friction of the machine, as referred to in paragraph 533, caused our records to indicate slightly heavier pressures than those actually received by the tool, and that the difference between the results of our experiments and the Manchester experiments can be explained in this way. Unquestionably this slight error in the frictional resistance tends towards recording pressures somewhat higher than the actual pressures; but since, as indicated in paragraph 533, the errors are proportional to the pressures, it is evident that it in no way accounts for the relative difference between thick and thin shavings in results obtained by the two sets of experiments. The following data further confirm this reasoning, and also the correctness of our conclusion that the pressure increases as the chip grows thinner.

550 In the comparison given below we have taken the data from two experiments made with the same tool upon the same piece of cast iron. (See Folder 13, Table 92)

DEPTH OF CUT	THICKNESS OF FEED	TOTAL SECTION OF CHIP	PRESSURE IN LB. ON TOOL PER SQUARE INCH OF SECTIONAL AREA OF CHIP
$\frac{1}{8}''$	0.0916	0.01145	102000
$\frac{27}{64}''$	0.0220	0.00928	117000

551 It will be noted that in both of these experiments chips having approximately the same sectional area were cut, but in one case a thin feed and a deep cut were used; while in the other case a thick feed and a shallow cut were used; and that in spite of the total areas being approximately the same, the thin feed was accompanied by a materially higher pressure per square inch than the thick feed.

552 In all such instances, it is clear that the frictional error, if any, caused by our apparatus is entirely eliminated as far as it affects thin or thick chips. Many more similar illustrations of this fact can be taken from the data recorded in the tables.

553 Further evidence confirming the fact that the pressure varies with the thickness of the shaving will be seen by referring to paragraph 559, and it should be noted also that in this matter the German experiments are in agreement with ours.

554 As stated above in paragraph 549, the Manchester experiments do not extend to feeds as fine as those taken in ours, and for this reason it is possible that the results obtained by them were in this particular misleading.

555 This paper is of necessity so voluminous that the subject of drilling metals will not be dealt with. But as confirming the conclusion drawn from our pressure experiment, that the pressure per square inch increases as the chip becomes thinner, we reproduce on Folder 12, Fig. 85, a diagram showing the results obtained by Professors Bird and Fairfield, of the Worcester Polytechnic Institute of Massachusetts, in their experiments on the power and pressure required in drilling cast iron, as published in the Transactions, Vol. 26, p. 362.

556 The diagram gives the twisting moments recorded in drilling a $\frac{3}{8}$-inch hole with feeds varying from 0.004 inch to 0.02 inch, and the curve shown represents the formula (developed by Mr. Barth),

$$M = 1470\ F^{\frac{1}{2}}$$

in which M = the twisting moment in inch-pounds; and
F = the feed in inches per revolution.

557 It is evident that this twisting moment is directly proportional to the pressure of the chip against the lips of the drill; and hence this resistance is also proportional to $F^{\frac{3}{5}}$. But this exponent $\frac{3}{5}$ is even smaller than the exponent $\frac{3}{4}$ for F in the formula developed by Mr. Barth to cover the results of our experiments on cutting pressures on cast iron (see paragraph 546), and thus indicates a proportionally still greater increase of the pressure with a decrease in thickness of the chip; or, what is the same thing, a proportionally still greater decrease in the pressure with an increase in the thickness of the chip.

558 This experiment confirms the results obtained by us that the pressure increases as the chip becomes thinner, as against the conclusions arrived at in the Manchester experiments.

THE EFFECT OF THE SIZE OF THE STANDARD TOOL UPON THE PRESSURE OF THE CHIP ON THE TOOL

559 On Folder 13, Fig. 90, are plotted the pressures obtained in cutting a piece of soft cast iron while using one of our standard $1\frac{1}{4}$-inch tools. On Folder 13, Fig. 89, are plotted a corresponding series of pressure determinations made upon the same piece of cast iron and using a $\frac{1}{2}$-inch tool. These two sets of experiments were purposely made upon exactly the same piece of cast iron to determine the effect of the size of the nose of the tool upon the pressure. The results very clearly confirm the conclusion given above, namely, that the pressure increases as the thickness of the chip diminishes.

560 Earlier in the paper we have indicated that in using a large sized tool with a given depth of cut and feed, the chip is thinner than in using a small tool, and that as the depth of cut increases, the difference in the thickness of the chip becomes more marked when taken by a large tool than by a small tool. Now, by referring to Folder 13, Fig. 90, with depth of cut of $\frac{17}{64}$ inch, in which a large tool was used, it will be noted that all of the spots lie almost directly upon the line of the curve, whereas by referring to the corresponding diagram, Folder 13, Fig. 89, for the small tool, it will be seen that these spots lie considerably below the line, thus showing lower pressures corresponding to a greater thickness of chip.

561 When shallow depths of cut are taken, there is comparatively little difference between the thickness of the chip as taken by the small tool and the large tool, and here it is obvious also that the pressures obtained with the two tools more nearly correspond.

THE EFFECT OF A THIN CHIP AND SHALLOW DEPTH OF CUT IN INCREASING THE PRESSURE ON THE TOOL IS THE SAME FOR HARD AS FOR SOFT CAST IRON

562 On Folder 13, Table 92, and Folder 13, Table 90, will be noted the actual pressures obtained in experiments, on the one hand, on soft cast iron, and on the other hand, on hard cast iron; and on Folder 13, Fig. 90, and Folder 13, Fig. 91, are recorded graphically the same data. These diagrams together with the formula beneath them, which represents the two sets of experiments, indicate that generally speaking the effect upon the pressure of chip on the tool of thinning the shaving and of making the depth of cut shallow is the same for hard as for soft cast iron. The only difference between the two is that the pressures are uniformly higher in cutting hard than in cutting soft cast iron. This fact will be seen in detail by a comparison of the following figures.

563 If we select from the table of pressures on the soft cast iron a light and heavy cut, and a similar light and heavy cut from the table for hard cast iron, as follows:

	DEPTH OF CUT IN INCHES	THICKNESS OF FEED IN INCHES	TOTAL SECTION OF CHIP IN SQUARE INCHES	PRESSURE IN LBS. ON TOOL PER SQUARE INCH OF SECTIONAL AREA OF CHIP
Soft Cast Iron	$\frac{1}{8}$	0.0635	0.00785	114000
	$\frac{3}{16}$	0.0909	0.05695	78000
Hard Cast Iron	$\frac{1}{8}$	0.064	0.008	178000
	$\frac{3}{16}$	0.09	0.05695	122000

564 It will be noted that the relative pressure on the chip in the two cases are approximately the same. This is indicated by the following proportion, the figures of which are taken from our tables:

Pressure per sq. in. soft cast iron thin chip (114-000) : Pressure per sq. in. soft cast iron thick chip (7800) = Pressure per sq. in. hard cast iron thin chip (178-000) : Pressure per sq. in. hard cast iron thick chip (122-000)

565 A comparison of the two formulæ given below for soft cast iron and hard cast iron show clearly that the ratio is the same between the two for the different hardnesses of iron.

For soft cast iron $P = 45000\ D^{\frac{1}{4}}\ F^{\frac{1}{2}}$

For hard cast iron $P = 69000\ D^{\frac{1}{4}}\ F^{\frac{1}{2}}$

or

$$\frac{69000\ D^{\frac{1}{4}}\ F^{\frac{1}{2}}}{45000\ D^{\frac{1}{4}}\ F^{\frac{1}{2}}} = 1.533$$

DETAILS OF EXPERIMENTS UPON THE PRESSURE OF THE CHIP ON THE TOOL IN CUTTING STEEL WITH OUR STANDARD TOOLS WITH VARIOUS FEEDS AND DEPTHS OF CUT

566 The following are the general conclusions arrived at on this subject:

567 (A) The total pressure of the chip on the tool in cutting steel of the different qualities experimented upon by us varies between the low limit of 92 tons (2000 lbs.) per square inch of sectional area of the chip, and the high limit of 168 tons (2000 lbs.) per square inch sectional area of the chip. (See Folder 12, Table 81)

568 (B) In cutting the same piece of steel, the pressure of the chip on the tool per square inch of sectional area of the chip grows very slightly greater as the chip becomes thinner, and is practically the same whether the cut is deep or shallow. See Folder 14, Table 99, from which are taken the following typical cases illustrating the relative pressures of a thin feed on the one hand and a coarse feed on the other.

Depth of cut $\frac{3}{16}$ inch $\times$ feed 0.0156 inch: Total pressure per sq. in. sectional area of chip, 295000

Depth of cut $\frac{3}{16}$ inch $\times$ feed 0.125 inch: Total pressure per sq. in. sectional area of chip 257000

569 (C) The same fact mathematically expressed is that in cutting the same piece of steel, the pressure of the chip on the tool per square inch of sectional area of the chip grows greater as the thickness of the chip grows less in proportion to (thickness of the feed)$^{\frac{1}{15}}$ or $F^{\frac{1}{15}}$. (See formula on Folder 14)

The pressure of the chip is in direct proportion to the depth of the cut.

570 (D) Within the limits of cutting speed in common use, the pressure of the chip upon the tool is the same whether fast or slow cutting speeds are used. (See paragraph 576)

571 (E) The pressure of the chip upon the tool depends but little upon the hardness or softness of the steel being cut, but increases as the quality of the steel grows finer. In other words, high grades of steel, whether soft or hard, give greater pressures on the tool than are given by inferior qualities of steel. (See paragraphs 503 and 511)

572 (F) The pressure of the chip on the tool per square inch of sectional area of the chip depends both upon the tensile strength of the steel and its percentage of stretch, and increases both as the tensile strength and stretch increase; although a higher tensile strength

has more effect than a large percentage of stretch in increasing the pressure. (See paragraphs 573 to 575)

573 Referring again to Folder 12, Table 81, upon the first, third and fourth horizontal lines of this table will be found data of three steel forgings, which are copied beneath in the order mentioned:

TENSILE STRENGTH IN TONS (2000 LBS.) PER SQUARE INCH	PERCENTAGE OF STRENGTH	PRESSURE ON THE CHIP TONS (2000 LBS.)	CUTTING SPEED IN FEET PER MINUTE
30	29	128	111
35	30	138	64
52	14	168	41

574 It will be noted that the percentage of stretch of the first and second of these forgings is about the same, whereas an increase of from 30 to 35 tons in the tensile strength of the metal is accompanied by an increase of from 128 to 138 tons pressure on the chip, showing an increase in the pressure on the chip with an increase of tensile strength.

575 Now, on comparing the hard forging, namely, the third on the list, it will be noted that as far as fineness of quality of metal is concerned, its physical tests show it to be about equal to that of the forging on the second line. It will be noted, however, that, as before pointed out, an increase in the percentage of stretch and an increase in the tensile strength both tend toward heavier pressures per square inch of sectional area of the chip upon the tool. By comparing the forgings on the second and third lines, however, it will be seen that an increase from 14 per cent to 30 per cent in the stretch has less effect upon the pressure on the tool than an increase from 35 tons to 52 tons in the tensile strength; thus making it clear that an increase in tensile strength has a greater effect upon the pressure of the chip on the tool than an increase in stretch. A further explanation of this fact will be found in paragraphs 508 to 511.

PRESSURE OF CHIP ON TOOL THE SAME WHETHER FAST OR SLOW CUTTING SPEEDS ARE USED

576 On Folder 14, Table 99, will be noted two sets of pressure experiments made upon steel of the same quality and with tools of

the same shape, one set with cutting speeds of 30 feet per minute and another set with cutting speeds of 60 feet per minute. An inspection of the corresponding figures in these two sets of experiments and an examination of Folder 14, Figs. 94 and 95, in which the same data are shown graphically, will indicate that, in general, doubling the cutting speed has no appreciable effect upon the pressure of the tool.

577 This is in substantial agreement with the results obtained in the Manchester experiments. Dr. Nicolson, in one set of dynamometer experiments, made with the same tool and the same piece of steel, obtained increasingly lower pressures on the tool for increases in the cutting speed.

578 On Folder 14, Fig. 93, we reproduce Fig. 342, taken from Dr. Nicolson's paper (published in Transactions, Vol. 25, p. 675).

579 In these experiments a feed of $\frac{1}{8}$ inch and a depth of cut of 0.35 inch was used. It will be observed that at normal cutting speeds there is a very slight diminution of pressures as the speed grows more rapid. In considering these experiments, however, the cut which was taken at 84 feet per minute should be left out, as in this case the cutting speed was so high that the tool was ruined in one minute and twelve seconds. It is, therefore, evident that this condition is so far from that of normal daily practice that it should not be considered in formulating a law. It will be noted also that at 60 feet cutting speed there are two experiments slightly at variance with the general trend of the rest of the data. On the whole, in these experiments there is close agreement between Dr. Nicolson's observations and our own.

580 As heretofore stated, owing to the voluminous nature of this paper, we shall not treat of the important subject of drilling or boring metals. We would, however, refer to a very elaborate and careful series of experiments by M. Codron published in "Bulletin de La Société D'Encouragement pour L'Industrie Nationale, 1903," probably the most elaborate series of experiments on drilling, boring and trepanning that have yet been published. M. Codron's experiments cover the pressures required to cut not only steels of various hardnesses, but also cast iron, bronze and other metals, and are made on almost all points with the thoroughness characterizing the work of all of our best modern French scientists.

POWER REQUIRED TO FEED THE TOOL

581 By far the most important conclusion arrived at by us in the field of "Pressure of the Chip on the Tool" is that the gearing designed in lathes, boring mills, etc., for feeding the tool should be

sufficiently strong to deliver at the nose of the tool A FEEDING PRESSURE EQUAL TO THE ENTIRE DRIVING PRESSURE OF THE CHIP UPON THE LIP SURFACE OF THE TOOL. This fact was developed by us in an experiment made in the year 1883 in the works of the Midvale Steel Company, and had such an important bearing upon the cost of turning out the product in the machine shop of those works that the results of this one simple investigation more than paid for all the experiments in the entire field of cutting metals undertaken in the Midvale Steel Works.

582 All of the lathes, boring mills, etc., purchased by this company from that time forward were fitted with feed gearing designed with power equal to the driving power of the machine, and in this way the many stoppages and delays so common in the average machine shop, due to broken feed gearing, were avoided. What is of even much greater importance, a lack of strength in the feed gearing never was accepted as an excuse on the part of any machinist for not taking the maximum cut on his machine.

583 When, fifteen years later, the writer started to reorganize the management of the Bethlehem Steel Company (a company in direct competition with the Midvale Steel Works and turning out a similar product), he was astounded to find that some of the leading tool builders of the United States who had been supplying extra strong feed motions with the machine tools furnished during this term of years to the Midvale Company, were selling machines fitted with far weaker feed gearing to the Bethlehem Company. On inquiring into the reason for this, he was informed that these tool builders had not even told the Bethlehem Company of the existence of lathes designed with extra heavy gearing, their reason being that they were certain that the Bethlehem Company would not be willing to pay any extra price for the more powerful feed gearing and it would only make them dissatisfied if they knew that they were not getting the most powerful machine built. The introduction of "task management" into the Bethlehem Steel Company, however, promptly developed the weakness in this particular of most of the machine tools in their shop.

584 In justice to one of the greatest engineers in this country, it should be said that all of the special machines designed under the supervision of Mr. John Fritz for the Bethlehem Steel Company were provided with feeding mechanism of ample power. The writer does not recall a single instance in which the feed motions of any of Mr. Fritz's machines broke when they were used to their maximum capacity under task management.

APPARATUS FOR DETERMINING THE POWER REQU RED TO FEED A TOOL

585 The following very simple apparatus was used in 1883 in our experiments upon the power required to feed the tool. On Folder 9, Fig. 52, will be seen a view of the vertical slide of a Wm. Sellers & Co. 84-inch diameter vertical boring mill. Upon the top surface of this vertical slide a wooden lever was made to bear upon a knife edge, the short end of the lever being held down by a chain connected with an I-bolt, and at the long end of the lever a receptacle was suspended into which weights were added until the required feeding force was obtained. The vertical slide was at first fed by means of its usual feeding screw. A loose washer, however, was fitted beneath the nut of this screw, and this was of course kept tight while the operation of feeding was performed with the regular feed gearing, and weights were added on the end of the wooden lever until the feeding was done by means of the lever instead of by the regular feed mechanism. The point at which this transfer of the feed took place was determined by finding when the washer just became loose. This was found to be quite a sensitive indication of the power required to feed.

586 The experiments were made upon a locomotive tire, the metal of which was about carbon 0.56 per cent, manganese 0.68 per cent, tensile strength 124,000 pounds, and 12 per cent to 14 per cent of stretch.

587 Tools with cutting edges varying from a straight edge at right angles to the direction of the feed to our standard round nosed tools, approximately, as illustrated in Folder 5, Fig. 24, were used, with a depth of cut varying from $\frac{1}{16}$ inch to $\frac{1}{4}$ inch, and the thickness of the feed varying from 0.0243 inch to 0.0774 inch. The pressure required to feed a square nosed tool was somewhat lighter than that required to feed our standard round nosed tool, and under average conditions as to the dullness of the tool, after eliminating the friction of the slide to which the tool was attached, the pressure upon the lip surface of the tool was found to be about 2.2 times the power required to feed the tool.

588 It should be noted, however, that the words "tool of average dullness" have a different meaning in our case from the same term as applied to tools in the average machine shop, since, as pointed out in paragraphs 189 and 197, it was our regular practice to use tools much duller on the average than those in common use in other shops. We ran at such relatively high cutting speeds that the cutting edges of our tools were soon rounded over, and this undoubtedly produced

higher feeding pressures than would be required for the ordinary sharp lathe tool.

589 However, before finishing our experiments it occurred to us that the normal power required to feed the tool was not the figure which should be used in designing machine tools, but that the maximum power which would ever be likely to be called for in feeding the tool was the only one to be used practically. This led to an experiment in which an exceedingly dull tool was used, such a tool as would only be allowed by a very careless machinist to continue under cut, but which condition was sooner or later sure to arise in the case of every machine tool throughout the shop.

590 The use just once of a scandalously dull tool in a machine would of course suffice to smash the feed gearing. An experiment made with a tool of this kind demonstrated the fact that to insure against breakage sufficient strength was called for in the feed gears to deliver at the nose of the tool a pressure equal to the total driving pressure of the chip upon the tool.

591 This one almost brutal experiment rendered all our more careful and accurate experiments of merely trifling interest.

592 When in 1904, the thoroughly scientific work of Dr. Nicolson in this field with his lathe tool dynamometer was published, it was with no little interest that we read his paper, feeling that in the end he was doomed to the same disappointment as to much of the scientific value of his work as we had experienced from ours. Unfortunately however, Dr. Nicolson's experiments were not extended to a scandalously dull tool, and for that reason readers of his paper must be warned against the adoption in tool design of the figures on feeding (or "traversing") pressure obtained by him. We do not of course state that the data in Dr. Nicolson's paper were not of great scientific interest, but merely that for the one perhaps most important purpose for which the experiments were undertaken his data should be disregarded.

COOLING THE TOOL WITH HEAVY STREAM OF WATER

EFFECT UPON THE CUTTING SPEED OF POURING A HEAVY STREAM OF WATER UPON THE CUTTING EDGE OF THE TOOL

593 Cooling the nose of a tool by throwing a heavy stream of water or other fluid directly upon the chip at the point where it is being removed by the tool from the steel forging enables the operator

to increase his cutting speed about 40 per cent.[1] The economy realized through this simple expedient is so large that it is a matter of the greatest surprise that experimenters on the art of cutting metals have entirely overlooked this source of gain. So far as the writer is aware, no experiments upon this subject have as yet been published. As explained in paragraph 35 (Part 1), in spite of the fact that (as a result of our experiments) the whole machine shop of the Midvale Steel Company was especially designed as long ago as 1893 for the use of a heavy stream of water (super-saturated with soda to prevent rusting) upon each cutting tool, until very recently practically no other shops in this country have been similarly equipped.

594 When one appreciates the very small gain in cutting speed, amounting perhaps to from 2 to 5 per cent, attained by the many experiments which have been made upon the exact angles to which tools should be ground, and also the small practical results realized from experiments upon the pressure of the chip on the tool, and when one realizes the large amount of time and expensive apparatus entailed in these experiments; and, on the other hand, the extreme simplicity of making experiments on the effect of cooling the tool, and the 40 per cent of gain from this source, it is indeed a matter of wonder that this element has been entirely neglected.

595 The following are the important conclusions arrived at as to the effect on the cutting speed of cooling the tool with a heavy stream of water.

596 (A) On Folder 15, Table 110, are summarized the results of our experiments upon the gain in cutting speed through the use of a heavy stream of water on the tool in cutting different qualities of metals with varying types of tools, namely, modern high speed chromium-tungsten tools, heated to the melting point, the old fashioned self-hardening tools, and carbon tempered tools.

597 The results obtained with modern high speed tools are the only ones of great practical interest at present, since no well managed machine shop would use any other than high speed cutting tools. The other data, however, are given as a matter of record and historic interest. (See paragraph 631)

598 (B) With high speed tools a gain of 40 per cent[1] can be made in cutting steel or wrought iron by throwing in the most advantageous manner a heavy stream of water upon the tool.

[1]See paragraphs 628 and 629 describing experiment made since writing this section of the paper.

599 In designing slide rules or tables, etc., for assigning daily tasks to machinists a 33 per cent increase in cutting steel or wrought iron should be allowed for instead of 40 per cent, owing to the fact that workmen are more or less careless in directing the stream of water to the proper spot upon the tool.

600 (C) A heavy stream of water (3 gallons per minute) for a 2-inch by 2½-inch tool and a smaller quantity as the tool grows smaller, should be thrown directly upon the chip at the point where it is being removed from the forging by the tool. Water thrown upon any other part of the tool or the forging is much less efficient. (See paragraphs 607 to 609)

601 (D) The gain in cutting speed through the use of water on the tool is practically the same for all qualities of steel from the softest to the hardest. (See Folder 15, Table 110)

602 (E) The percentage of gain in cutting speed through the use of water on the tool is practically the same whether thin or thick chips are being removed by the tool. (See paragraph 630)

603 (F) With modern high speed tools a gain of 16 per cent can be made by throwing a heavy stream of water on the chip in cutting CAST IRON. (See paragraphs 625 to 627)

604 (G) To get the proper economy from the use of water in cooling the tool, the machine shop should be especially designed and the machine tools especially set with a view to the proper and convenient use of water. (See paragraphs 610 to 616)

605 (H) In cutting steel, the better the quality of tool steel, the greater the percentage of gain through the use of a heavy stream of water thrown directly upon the chip at the point where it is being removed from the forging by the tool. The gain for the different types of tools in cutting steel is:

a Modern high speed tools 40 per cent;
b Old style self-hardening tools 33 per cent;
c Carbon tempered tools 25 per cent.

606 This fact, stated in different form, is that: The hotter the nose of the tool becomes through the friction of the chip, the greater is the percentage of gain through the use of water on the tool. (See Folder 15, Table 110 and paragraph 631)

THE PORTION OF THE TOOL ON WHICH THE WATER JET SHOULD BE THROWN

607 A series of experiments has demonstrated that water thrown directly upon the chip at the point where it is being removed from

the forging by the tool will give higher cutting speeds than if used in any other way.

608 As another illustration of the small value to be attached to theories which have not been proved, we would cite the following: After deciding to try experiments upon the cooling effect of water when used upon a tool, it was our judgment that if a stream of water were thrown upward between the clearance flank of the tool and the forging itself in this way the water would reach almost to the cutting edge of the tool at the part where it most requires cooling, and that, by this means the maximum cooling effect of the water would be realized. We, therefore, arranged for a strong water jet to be thrown, as shown on Folder 7, Fig. 40b, between the clearance flan kof the tool and the flank of the forging, and made a series of experiments to determine the cooling effect of water with various feeds and depths of cut. So confident were we of the truth of this theory that we did not deem it worth while to experiment with throwing streams of water in any other way, until months afterward, when upon throwing a stream of water upon the chip directly at the point where it is being removed from the forging by the tool, we found a material increase in the cutting speed, and thus our first experiments were rendered valueless.

609 Practically, great difficulty will be found in getting machinists in the average shop to direct the stream of water on to the chip in the proper way as indicated on Folder 7, Fig. 40a, because when a sufficiently heavy stream of water is thrown upon the work at this point it splashes much more than when thrown upon the forging just above the chip; and the machinists prefer slower cutting speeds and less splash. However, when they are managed under the "task system" with trained speed bosses who are accustomed to obeying orders, this trouble disappears.

FORTY PER CENT GAIN IN CUTTING SPEED FROM THROWING A HEAVY STREAM OF WATER UPON THE TOOL IN CUTTING STEEL

910 It has been customary for many years to use under certain circumstances, a small trickling stream of water upon cutting tools (mostly on finishing tools, and with the object of giving the work what is called a "water finish"). For this purpose a small water can is generally mounted upon the saddle of the machine above the tool, and refilled from time to time by the machinist. Such streams of water, however, have little or no effect in increasing the cutting speed because they are too small in volume to appreciably cool the nose of the tool.

611 The most satisfactory results are obtained from a stream of

water falling at rather slow velocity, but with large volume, at the proper point upon the tool; since a stream of this sort covers a larger area of the tool and is much freer from splash.

612 This water supply should be delivered through pipes fitted up with universal friction joints, so that the apparatus can be quickly adjusted to deliver the water at any desired point (the pipe being supported by a rigid bracket attached to the saddle of the lathe, preferably on the back side so as to be out of the way). In the case of short lathe beds the water supply can be delivered from overhead through a rubber hose, and in the case of long lathe beds through telescoping pipes attached to the saddle (smooth drawn brass pipes telescoping inside of ordinary wrought iron pipes, with suitable stuffing boxes being used).

613 About three gallons of water per minute are required for adequately cooling a very large roughing tool, say, 2 inches by 2½ inches section; and proportionally smaller quantities as the tool grows smaller.

614 For economy, the same water should be use over and over again, and it should be supersaturated with soda to prevent the machines from rusting. Wrought iron pipes about 1¼ inches diameter should lead the water from beneath the machine below the floor to the main soda water drains at the side of the shop. These drains are made of pipe from 3½ to 5 inches in diameter, with a chain extending through them from one end to the other, the chain being twice as long as the drain through which it extends. In case of sediment forming in this pipe or in case of chips passing by the double sets of screens and double settling pots which should be supplied at each machine, the drain can be quickly cleaned by pulling the chain backward and forward through it once or twice.

615 The soda water is returned through this system of underground piping to a large central underground tank, from which it is pumped through a small, positive, continuously running pump, driven by the main line of shafting, into an overhead tank with overflow which keeps the overhead soda water supply mains continually filled and under a uniform head. If the shop is constructed with a concrete floor, a catch basin for the water can be molded in the concrete directly beneath each machine. Otherwise, each machine should be set in a large wrought iron pan or shallow receptacle which catches the soda water and the chips. In both cases, however, two successive settling pots—independently screened so as to prevent the chips, as far as possible, from getting into the return main—are required beneath each machine.

616 The ends of the 1¼ inch wrought iron pipes which lead the water from the machines to a large drain at the side of the shop should be curved up with a sweeping curve so that their outer ends come close to the top of the floor of the shop. The sediment and chips must be cleaned from these pipes from time to time by means of a long round steel rod from ⅜ to ½ inch in diameter, which, after removing the plug at the outer end of the drain pipes, is shoved through the pipe. Apparatus of this type has been in successful use for about 23 years with no trouble from clogging.

DETAILS OF TYPICAL EXPERIMENT FOR DETERMINING GAIN THROUGH HEAVY STREAM OF WATER ON THE TOOL

617 The following is a detailed description of one of our series of experiments on the effect of water on the tool, made in this case for the purpose of determining the gain from the use of a heavy stream of water in cutting an exceedingly hard bar of metal, especially made and hammer hardened so as to be harder than hard steel of any of the qualities usually met with in machine shop practice. This experiment is given in detail as a type of our best method of experimenting in cases of this kind. The following are the physical tests and the chemical composition of the steel bar experimented upon.

EXPERIMENT BEGAN NOVEMBER 23, 1899

TENSILE STRENGTH	ELASTIC LIMIT	EXTENSION	CONTRACTION	APPEARANCE OF FRACTURE
LBS. 102,270	71,590	PER CENT 1.00	PER CENT 0.75	CRYSTALLINE

CARBON PER CENT	SILICON PER CENT	MANGANESE PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT
1.05	0.147	0.86	0.027	0.034

This bar was hammer hardened.

618 Tools of the shape shown on Folder 5, Fig. 24, were made from tool steel of the following chemical composition, and were treated by the Taylor-White process (*i. e.*, heated to the melting point, cooled down, and reheated to 1150 degrees in a lead bath):

TUNGSTEN PER CENT	CHROMIUM PER CENT	CARBON PER CENT	MANGANESE PER CENT	SILICON PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT
8.00	3.90	1.90	0.30	0.20	0.025	0.030

These tools were marked respectively V_1, V_2, U_3, U_4, U_6. They were then all standardized to prove their uniformity by being run at a cutting speed of 16 feet per minute, duration of cut 20 minutes, feed $\frac{1}{16}$ inch, depth of cut $\frac{3}{16}$ inch. The ruining speed upon this forging of tools of this type had been previously proved to be between 16 and 17 feet per minute. The following are the details of the experiments with water:

EXPERIMENTS WITH WATER

TEST NUMBER	MARK ON TOOL	CUTTING SPEED FEET	DURATION OF CUT MINUTES	CONDITION OF TOOL AT END OF RUN
256 b	V_1	19	20	fair
257 b	V_2	20	20	fair
258 b	U_3	21	20	fair
259 b	U_4	22	20	good
260 b	U_6	23	20	fair
261 b	V_1	24	2	ruined
262 b	U_3	23	1½	ruined
263 b	U_4	23	15½	ruined
264 b	V_2	22	7	ruined
265 b	U_3	22	20	nearly ruined
266 b	V_1	22	15	ruined
267 b	V_1	21	17½	ruined
268 b	V_2	21	20	nearly ruined
269 b	U_6	24	4	ruined
270 b	U_6	20	2½	ruined
271 b	V_1	20	20	nearly ruined

619 From the list given above are below extracted those experiments that show the highest speed at which each tool endured 20 minutes and also the length of time it endured before ruining at one foot higher speed.

TEST NUMBER	MARK ON TOOL	CUTTING SPEED PER MINUTE FEET	DURATION OF CUT MINUTES
271 b	V_1	20	20
267 b		21	17½
268 b	V_2	21	20
264 b		22	7
265 b	U_3	22	20
262 b		23	1½
259 b	U_4	22	20
263 b		23	15½
260 b	U_6	23	20
296 b		24	4

EXPERIMENTS WITH WATER

620 In test No. 261 b tool V_1 had been ruined at a speed of 24 feet and thereby, as was afterward ascertained, suffered a marked deterioration. This accounts for the lower maximum speed at which it subsequently stood up.

621 In order to fully ascertain whether the ruining of these tools with water had any marked injurious effect upon them, the following tests were made without the use of water on the second day of the experiments:

TOOL NO.	MARK ON TOOL	CUTTING SPEED MINUTES	DURATION OF CUT MINUTES	CONDITION OF TOOL AT END OF RUN
272 b	U_4	16	20	nearly ruined
273 b	U_5	16	20	fair
274 b	U_6	16	20	fair
275 b	V_2	16	less than 20	ruined*
276 b	V_1	14	less than 20	ruined*
277 b	V_2	14	less than 20	ruined*

* Tools V_1 and V_2 had evidently suffered considerably, due to their ruining tests while finding their proper speeds under water, and ought therefore to be left out of consideration. As the V_1 and V_2 tools had evidently been injured during their test with water, the results obtained were not taken in the average.

622 The average cutting speeds of the U tools (all of which were proved to be uninjured) were as follows:

$$\frac{22+22+23}{3}=22.33 \text{ feet},$$

which divided by 16 feet gives 1.416 to 1.0 as the gain made by using water on the tool.

623 A similar experiment to the above was made upon a steel bar of about the following chemical composition and physical qualities and annealed at 1300 degrees Fahr.:

CARBON PER CENT	MANGANESE PER CENT	SILICON PER CENT	SULPHUR PER CENT	PHOSPHORUS PER CENT
.34	.54	.176	.026	.037

TENSILE STRENGTH POUND	ELASTIC LIMIT POUND	PERCENTAGE OF STRETCH PER CENT	PERCENTAGE OF CONTRACTION OF AREA PER CENT
70,000	34,000	29	44

624 Taylor-White tools similar to those described above, having been carefully standardized, showed a cutting speed when run without

water of 60 feet per minute, and when run under a heavy stream of water of 83 feet, thus indicating a gain of 1.39 to 1.0 from the use of water. The average gain then through the use of water on the tool for hard and soft forgings is about 40 per cent.

SIXTEEN PER CENT GAIN IN CUTTING SPEED FROM THROWING A HEAVY STREAM OF WATER UPON THE TOOL IN CUTTING CAST IRON

625 In 1906 after the writing of this paper was well under way it occurred to us that we had accepted as true without verification through accurate experiments the fact that water could not be used in cutting cast iron. This is another of the many instances in which an absolutely erroneous opinion prevails throughout all of our machine shops without any foundation in fact. It is likely, however, that this opinion has become so firmly rooted in the minds of all mechanics and foremen from the fact that a water finish cannot be made on cast iron, while it is in many cases most desirable for steel.

626 To determine the effect of a heavy stream of water in cooling a tool cutting cast iron, experiments (similar to those described above) were made by us during the summer and fall of 1906 on a test piece consisting of exceedingly hard cast iron with cutting tools of three different chemical compositions. The piece of cast iron is the same as that marked "hard cast iron" on Folder 20, Table 138.

627 The chemical composition of three of the latest high speed tools experimented with was that of tools Nos. 2, 5 and 7 (Folder 20, Table 138). The following tabl erepresents the average gain made by these tools when they were run with a heavy stream of water as compared with running under exactly the same conditions dry. Depth of cut $\frac{3}{16}$ inch, feed $\frac{1}{16}$ inch, standard 20-minute cut; tools used, our standard $\frac{7}{8}$ inch (shown Folder 5, Fig. 24)

Cutting speed without water	47 ft.
Cutting speed with heavy stream of water	54 ft. 7 ins.
Gain through use of water	16 per cent

628 Since writing the section of the paper covering the whole subject of the gain by cooling the tool with water, we have again met in our experiments with one of the strange anomalies which characterize the laws governing the art of cutting metals.

629 When the best of the modern high speed tools, namely, tool No. 1, Folder 20, Table 138, was run with a heavy stream of water in cutting the hard forging referred to in the same table, it was shown that instead of a gain of 41 per cent through the use of water, as had been obtained with tools differing in their chemical composition, as referred to in paragraphs 610 to 630, that there was a gain through the use of

water of only 15 per cent. A lack of time prevented our going more fully into the effect of water upon high speed steels of the most modern composition with medium and soft forgings. It is, therefore, manifestly of the greatest importance to carry on thorough experiments in this field. Our experiments with tool No. 1 gave the following data:

Depth of Cut $\frac{3}{16}$ Inch. Feed $\frac{1}{16}$ Inch. Standard 20-minute cut.

Cutting speed without water .....41 ft. 5 in.
Cutting speed with water.....47 ft. 8 in.
Gain through use of water ..... .15 per cent

THE PERCENTAGE OF GAIN THE SAME WHETHER THIN OR THICK CHIPS ARE BEING REMOVED

630 When in the Midvale Steel Works the gain in cutting speed through the use of water on the tool was discovered in 1884, a thorough investigation was made with varying depths of cut and thickness of feed—carbon tempered tools being used in cutting steel tires —and it was found that the percentage of gain in cutting speed through the use of water was the same whether the chips were thick or thin. These experiments have not been repeated by us with high speed tools, and it is possible that, owing to the very great difference in the heat of the high speed and the carbon tempered tools, there is a different ratio of gain for thick and thin chips with high speed tools. However, our slide rules have been in practical use in cutting chips of all degrees of thickness for years, using water on the tool, with the same ratio of increase in speed for thick and thin chips; and it would seem if any material difference exists between the gain in thick and thin chips, that this fact would have become evident through the failure of our slide rules to indicate the proper speeds. A careful experiment on this point is desirable.

631 In 1894–95 experiments were made with a carbon tempered tool containing 1.6 per cent chromium and with tools made from old fashioned self-hardening Midvale steel, of the following chemical composition:

	CARBON PER CENT	SILICON PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT	MANGANESE PER CENT	CHROMIUM PER CENT	TUNGSTEN PER CENT
MIDVALE	1.143	0.246	0.023	0.008	0.180	1.830	7.723

632 The carbon tempered tools showed an average gain of 25 per cent in cutting a hard steel forging of the following physical and chemical properties:

TENSILE STRENGTH POUNDS	ELASTIC LIMIT POUNDS	STRETCH PER CENT	CONTRACTION OF AREA PER CENT
115,000	58,000	15.6	31.4

CARBON PER CENT	SILICON PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT	MANGANESE PER CENT	COPPER PER CENT
.555	.236	.049	.031	.981	.058

The Mushet and Midvale self-hardening tools showed an average gain of 30 per cent in cutting the same forging. From these figures it will be noted that as the cutting speeds of tools grow higher, the percentage of gain through the use of water for cooling the tool grows greater. This would seem to be due to the fact that (taking the two extremes) the noses of the modern high speed tools are very much hotter under the great friction caused by the high speed of the chip than are the old fashioned tempered tools with their slow speeds, and that therefore the water acts in a considerably more efficient manner in cooling the high speed tools than the slow speed tools.

CHATTER OF THE TOOL

633 The following are the general conclusions arrived at on the subject of chatter of the tool:

CHATTER CAUSED BY THE NATURE OF THE WORK

634 (A) Chatter is the most obscure and delicate of all problems facing the machinist, and in the case of castings and forgings of miscellaneous shapes probably no rules or formulæ can be devised which will accurately guide the machinist in taking the maximum cuts and speeds possible without producing chatter. (See paragraph 648)

635 (B) It is economical to use a steady rest in turning any piece of cylindrical work whose length is more than twelve times its diameter. (See paragraph 669)

CHATTER CAUSED BY THE METHOD OF DRIVING THE WORK

636 (C) Too small lathe-dogs or clamps or an imperfect bearing at the points at which the clamps are driven by face plate produce vibration. (See paragraph 659)

CHATTER CAUSED BY CUTTING TOOLS

637 (D) To avoid chatter, tools should have cutting edges with curved outlines and the radius of curvature of the cutting edge should

be small in proportion as the work to be operated on is small. The reason for this is that the tendency of chatter is much greater when the chip is uniform in thickness throughout, and that tools with curved cutting edges produce chips which vary in thickness, while those with straight cuttinge dges produce chips uniform in thickness. (See paragraph 661)

638 (E) Chatter can be avoided, even in tools with straight cutting edges by using two or more tools at the same time in the same machine. (See paragraphs 664 and 665)

639 (F) The bottom of the tool should have a true, solid bearing on the tool support which should extend forward almost directly beneath the cutting edge. (See paragraph 663)

640 (G) The body of the tool should be greater in depth than its width. (See paragraph 662)

CHATTER CONNECTED WITH THE DESIGN OF THE MACHINE

641 Chatter caused by modifications in the machine may be classified as follows:

642 (*H*) It is sometimes caused by badly made or fitted gears.

643 (*J*) Shafts may be too small in diameter or too great in length.

644 (*K*) Loose fits in the bearings and slides may occasion chatter.

645 (*L*) In order to absorb vibrations caused by high speeds, machine parts should be massive far beyond the metal required for strength. (See paragraph 656)

THE EFFECT OF CHATTER UPON THE CUTTING SPEED OF THE TOOL

646 (*M*) Chatter of the tool necessitates cutting speeds from 10 to 15 per cent slower than those taken without chatter, whether tools are run with or without water. (See paragraphs 671 to 677)

647 (*N*) Higher cutting speed can be used with an intermittent cut than with a steady cut. (See paragraphs 678 to 680)

648 Of all the difficulties met with by a machinist in cutting metals, the causes for the chatter of the tool are perhaps the most obscure and difficult to ascertain, and in many cases the remedy is only to be found after trying (almost at random) half a dozen expedients.

649 This paper is chiefly concerned with chatter as it is produced or modified by the cutting tool itself. Some of the other causes for chatter, however, may be briefly referred to. These may be divided into five groups:

(A) The design of the machine;
(B) the nature and proportions of the work being operated upon;
(C) the care and adjustment of the parts of the machine;
(D) the method of setting the work in the machine or of driving it;
(E) the shape of the cutting tools, manner in which they are set in the machine and the speeds at which they are run.

Causes (A) and (B) are outside the control of the machinist. Elements (C), (D) and (E) are or should be to a large extent under the control of the management of the shop.

650 (A) Referring, now, to cause (A), "The design of the machine" the chief elements causing chatter in the design of a machine are:

651 (Aa) Gears which are set out of proper adjustment or the teeth of which are untrue. It should be noted that involute teeth will run smoothly whether their pitch diameters exactly coincide or not, whereas the epicycloidal teeth are almost sure to rattle unless their pitch lines are maintained in their exact proper relations one to the other.

652 (Ab) Chatter is frequently caused through mounting the driving gears upon shafts which are either too small in diameter or too long. A large excess in the diameter of shafts beyond that required for strength is called for in order to avoid torsional deflection which produces chatter.

653 (Ac) Lathe shafts and spindles must of course be very accurately and closely fitted in their bearings, and the caps adjusted so as to avoid all play.

654 (Ad) For heavy work the lathe tail stocks should be fastened to the bed plates with bolts of very large diameter, and should be tightened down with long handled wrenches.

655 (Ae) The lathe bed itself should be exceedingly massive, and should contain far more metal than is required for strength or even to resist ordinary deflections; and the moving tool supports should also be heavy far beyond what is required for strength.

MASSIVE MACHINES NEEDED FOR HIGH SPEEDS

656 Undoubtedly high cutting speeds tend far more than slow speeds toward producing minute and rapid vibrations in all parts of the machine, and these vibrations are best opposed and absorbed by having large masses of metal supporting the cutting tool and the head and tail stocks. It is largely for the purpose of avoiding vibration and

chatter in machines that the high cutting speeds accompanying the modern high speed tools call for a redesigning of our machine tools. While it is true that in many cases a very great gain can be made by merely speeding up a machine originally designed for slow speed tools, this increase in speed almost invariably produces a corresponding increase in the vibration or chatter, and for absorbing this, the lathes and machines of older design are, in many cases, too light throughout.

657 (C) Cause (C) namely, "The care and proper adjustment of the various parts of the machine" is almost entirely under the control of the shop management. It is of course evident that so far as the effect of chatter is concerned, one of the most important causes can be eliminated from the shop by systematically looking after the careful adjustment of all of the working parts of the machine to see that the caps of the bearings are always so adjusted as to have no lost motion and yet not bind, and so that all gibs and wedges for taking up wear upon the various slides are kept adjusted to a snug fit. It is our experience, however, that the adjustment of the various parts of the machine should in no case be left to the machinist who runs his lathe, but that the adjustment and care of machines should be attended to systematically and at regular intervals by the management. In large shops a repair boss with one or two men can be profitably kept steadily occupied with this work. A tickler, however, should be used for reminding the repair boss each day of the adjustment of machines and the overhauling which should be attended to on that day.

658 (D) Cause (D), namely, "The method of setting the work in the machine or of driving it," is in many cases capable of being directly under the control of the machinist.

659 (Da) One of the most frequent causes for chatter lies either in having too light or too springy clamps or lathe dogs fastened to the work for the purpose of driving it, or in having vibration at the point of contact between the lathe dog, and the face plate of the lathe, or the driving bracket which is clamped to it. In heavy work the clamps should be driven at two points on opposite sides of the face plate, and great care should be taken to insure a uniform bearing of the clamps at both of these driving points. Chatter through vibration at this point can frequently be stopped by inserting a piece of leather or thick lead between the clamps and the driving brackets on the face plate; which has the effect both of deadening the vibration and equalizing the pressure between the two outside diameters at which the clamp is driven by the face plate.

660 (Db) A dead center badly adjusted so as to be either too tight or too loose on the center of the work, or any lost motion in the

tail stock of the lathe is such an evident source of chatter that it need not be dwelt upon.

661 (E) Cause (E) namely, "The shape of the cutting tools, the manner in which they are set in the machine and the speeds at which they are run." In paragraphs 312 and 315 we have attempted to explain the effect of a uniform thickness of chip in causing chatter, and have indicated that the proper remedy for this is to use a round nosed tool, which is always accompanied by a chip of uneven thickness.

662 In paragraphs 415 and 425 we have also referred to the desirability of having the body of tools deeper than their width in order to insure strength as well as to diminish the downward deflection of the tool, which frequently results in chatter, particularly when the tools are set with a considerable overhang beyond their bearing in the tool post.

663 In paragraphs 450 and 459 we have also called attention to the great desirability of designing tools with their bottom surfaces extending out almost directly beneath the cutting edge, and of truing up the bottom surface of the tools, so as to have a good bearing directly beneath the nose of the tool on the tool support. If sufficient care is taken in the smith shop and the smith is supplied with a proper surface plate, the tools can be dressed so as to be sufficiently true on their bottom surfaces for all ordinary lathe work.

664 As indicated in paragraphs 315 to 325, it has been the necessity for avoidance of chatter which has influenced us greatly in the adoption of round nosed tools as our standard. As shown in paragraph 312, tools with straight cutting edges, which remove chips uniform throughout in thickness can be run at very much higher cutting speeds than our standard round nosed tools; but owing to the danger of chatter, from these tools, their use is greatly limited, in fact, almost restricted to those speecial cases in which chatter is least likely to occur. Attention should be called, however, to a method by which straight edge tools have been used successfully for many years upon work with which there was a very marked tendency to chatter.

665 While at the works of the Midvale Steel Company we superintended the design of a large lathe for rough turning gun tubes and long steel shafts; in which tools with long straight cutting edges were used without chatter, and yet at the high speeds corresponding to the thin chips which accompany this type of tool. This lathe was designed with saddle and tool posts of special construction, so that two independently adjustable tool supports were mounted on the front side of

the lathe and one on the back side. In each of these slides a heavy straight edge tool was clamped. The three tools were then adjusted so that they all three removed layers of metal of about equal thickness from the forging, and, although the tendency toward chatter,—owing to the uniform thickness of the chip,—as indicated in paragraph 315, was doubtless as great with these straight edge tools as with any others, the period of maximum or of minimum pressure for all three tools never corresponded or synchronized so that when one tool was under maximum pressure, one of the others was likely to be under minimum pressure. For this reason the total pressure of the chips on all three tools remained approximately uniform and chatter from this cause was avoided.

666 (B) Cause (B), namely, "The nature and proportions of the work being operated upon."

667 In assigning daily tasks to each machinist with the help of our slide rules, the element which still continues to give the greatest trouble to the men who write out these instructions is deciding just how heavy a cut can be taken on the lighter and less rigid classes of work without causing chatter. This branch of the art of cutting metals has received less careful and scientific study than perhaps any other. While the element is one which must always remain more or less under the domain of "rule of thumb," since the causes which produce chatter, particularly in castings of irregular shapes, are so many and complicated as to render improbable their successful reduction to general laws or formulæ, undoubtedly much can be done toward attaining a more exact knowledge of this subject, and experiments in this line present a most important field of investigation.

668 The following rule (belonging to the order of "rule of thumb") which has been adopted by us after much careful and systematic observation, extends over work both large and small, and covers a wide range:

IT IS ECONOMICAL TO USE A STEADY REST IN TURNING ANY PIECE OF METAL WHOSE LENGTH IS MORE THAN TWELVE TIMES ITS DIAMETER

669 When the length of a piece becomes greater than twelve times its diameter, it is necessary to reduce the size of the cut to such an extent that more time will be lost through being obliged to use a light cut than is required to properly adjust a steady rest for supporting the piece.

670 There is one cause for chatter which would seem to be impos-

sible to foresee and to guard against in advance; *i. e.*, chatter which is produced by a combination of two or more of the several elements likely to cause chatter. If, for instance, the natural periods for vibration in the tool and in the work or in any of the parts of the lathe and the work happen to coincide or synchronize, then chatter is almost sure to follow; and the only remedy for this form of chatter seems to lie in a complete change of cutting conditions; a change, for instance, to a coarser feed with an accompanying slower cutting speed, or vice versa. Unfortunately, for economy, higher speeds rather than slow speeds tend to produce this type of chatter, and the remedy therefore generally involves a slower cutting speed.

THE EFFECT OF CHATTER UPON THE CUTTING SPEED

671 A tool which chatters to any great extent must be run at a rather slower cutting speed than a tool which runs free from chatter, as will be seen by the following carefully tried experiment:

672 A forging, 14 feet long, $4\frac{5}{8}$ inches diameter, made out of exceedingly hard steel which was especially hammer hardened and uniform, was placed in the lathe, and standard cuts $\frac{3}{16}$ inch depth, and $\frac{1}{16}$ inch feed (with our standard round nosed tool $\frac{7}{8}$ inch) were taken upon it in such a way that they first ran smoothly without chattering; other cuts were then taken in such a position on the forging that the tool chattered badly throughout its cut. This was accomplished by using a steady rest in one case so as to prevent chatter, and in the other case running without the steady rest. All of the tools had been carefully standardized before starting the experiments, and proved uniform and capable of running at maximum cutting speeds. The forging had also been proved uniform, and its standard cutting speed had been shown to be between $15\frac{1}{2}$ and 16 feet per minute.

673 In the two tables below in paragraph 674 are given the details of the cutting speeds obtained with and without chatter. In one of these experiments the tool was run without water and in the other the tool was cooled through the use of a heavy stream of water.

674 An examination of the results of this experiment indicates in general that chatter causes a reduction in cutting speed of from 10 per cent to 15 per cent whether tools are run without water or with a heavy stream of water to cool them.

675 The following EXPERIMENTS SHOW THAT CHATTER CAUSES A REDUCTION IN CUTTING SPEED OF 10 PER CENT TO 15 PER CENT WHETHER THE TOOLS ARE RUN WITH OR WITHOUT WATER TO COOL THEM. (See paragraphs 671 to 676)

CHATTER CAUSES REDUCTION 10 TO 15 PER CENT IN CUTTING SPEED

NO WATER ON THE TOOL

TEST NO.	MARK ON TOOL	CUTTING SPEED	DURATION OF CUT	CONDITION OF TOOL AT END OF RUN	WHETHER TOOL CHATTERED OR NOT
		ft. in.	min.		
124 b	U_8	15	20	good	no chatter
125 b	U_8	17 6	14½	ruined	no chatter
126 b	U_8	15	4½	ruined	chattered badly
127 b	U_8	15	9½	ruined	chattered badly

WATER ON THE TOOL

TEST NO.	MARK ON TOOL	CUTTING SPEED	DURATION OF CUT	CONDITION OF TOOL AT END OF RUN	WHETHER TOOL CHATTERED OR NOT
		ft.	min.		
128 b	U_{10}	19	5½	ruined	chattered badly
129 b	U_{10}	19	20	fair	no chatter

676 Experiment No. 125b was made for the purpose of again showing conclusively that both the tool and the forging had been properly standardized. It will be noted that this tool, free from chatter, broke down in 14½ minutes at a cutting speed of 17 feet 6 inches, whereas the tool just above it ran all right for 15 feet at 20 minutes, showing that both the forging and tools had been properly standardized.

677 Accurate experiments on the chatter of the tool are difficult to make because the comparatively small diameter of work which is needed to insure chatter calls for an extremely hard piece of metal (*i. e.*, slow cutting speeds) in order to make the runs, which must last for 20 minutes, extend through a sufficiently short distance over the length of the forging so that the tools shall not be in danger of chattering. It was for this reason that we were obliged to make the above forging out of extremely hard metal.

HIGHER CUTTING SPEED CAN BE USED WITH AN INTERMITTENT CUT THAN WITH A STEADY CUT

678 An intermittent cut, however, has a very different effect upon cutting speed from that produced by chatter. We have observed in a large number of cases that when a tool is used in cutting steel with a

heavy stream of water on it (and this is the proper method of cutting steel of all qualities), a rather higher cutting speed can be used with an intermittent cut than with a steady one. The reason for this is that during that portion of the time when the tool is not cutting, the water runs directly on those portions of the lip surface and cutting edge of the tool which do the work and for this reason the tool is more effectively cooled with intermittent work than with steady work. As an example of intermittent work, the writer would cite:

a cutting the outside diameter of a steel gear wheel casting, in which case the tool is only one-half its time under cut;

b or turning small pieces of metal which are greatly eccentric;

c or, for example, all planer and shaper work which is not too long.

679 It would seem from a theoretical standpoint that a tool would be greatly damaged (and therefore a slow cutting speed would be called for) by the constant series of blows which its cutting edge receives through intermittent work. It will be remembered, however, that in planer work (and this class of intermittent work comes to the direct attention of every machinist), the tool is more frequently injured while dragging backward on the reverse stroke of the planer than it is while cutting, and it is very seldom that a tool is damaged as it starts to cut on its forward stroke. In all cases, however, where the tool deflects very greatly, when it starts its cut on intermittent work slower speeds are called for than would be required for steady work.

680 The above remarks on intermittent work do not, of course, apply to cast iron with a hard scale or the surface of which is gritty. It is evident that in all such cases owing to the abrasive action of the sand or scale on the tool, intermittent work is much more severe upon the tool than a steady cut.

HOW LONG SHOULD A TOOL RUN BEFORE REGRINDING?

THE EFFECT UPON THE CUTTING SPEED OF THE DURATION OF THE CUT; I. E., THE TIME WHICH THE TOOL MUST LAST UNDER PRESSURE OF THE CHIP WITHOUT BEING REGROUND

681 The following are the principal conclusions arrived at on this subject, regarding the duration of the cut:

682 (A) For a practical table showing how long each sized tool

should be run before being reground, see Folder 15, Table 108. (See paragraphs 710 to 728)

683 (B) For reasons for running tool the length of time given in the practical table referred to in Conclusion A, see paragraphs 710 to 717.

684 (C) If we note the proper cutting speed for a tool which is to last 20 minutes, and wish to find the cutting speed for a tool to last 40 minutes, multiply the 20 minute cut by 0.92. (See paragraph 701)

685 (D) If we have the proper cutting speed for a tool to last 20 minutes, and wish to find the proper cutting speed for a tool to last 80 minutes, multiply the 20-minute cut by 0.84. (See paragraph 701.)

686 (E) For a practical table giving the ratios between the cutting speeds corresponding to different durations of cut, see Folder 15, Table 105. (See paragraphs 696 to 704)

687 (F) For formula from which practical table in (A) was made up, see Folder 15, Table 103; diagram 104; and description, paragraph 700.

688 (G) The same relation exists between the duration of the cut and the cutting speed for steels of different degrees of hardness. (See paragraph 705)

689 (H) No scientific or correct conclusions can be drawn from tests in the art of cutting metals in which cuts of much shorter duration than 20 minutes are used. (See paragraphs 703 and 704)

690 (J) We have been unable to accurately determine the relation between the duration of the cut and the cutting speed for tools used in cutting cast iron. Such laws are badly needed. (See paragraph 709)

691 (K) For the relation of the duration of cut to cutting speed when carbon tempered tools are used, see Folder 15, Table 107; diagram 106; paragraphs 706 and 707)

692 (L) Modern high speed tools do a very much larger amount of work without regrinding than carbon tempered tools. The effect upon the cutting speed of the duration of the cut, modern high speed tools and carbon tools compared. (See paragraph 708)

693 In paragraph 149, we have called attention to the fact that as a measure of the value of a tool, the length of time which a tool can be run without being reground is a false and worthless standard; and in paragraphs 177 to 182, we have called particular attention to the radically different kind of wear which occurs with tools that last only a short while under cut and those which last for a longer time.

694 Briefly restated, the reason for this is that in order to have it last a long time, any given tool must be run at so slow a cutting speed

as to waste the time of both the machinist and the machine. The small saving in grinder's wages, in the wages of the smith and in tool steel, which is made by having a tool last a very long time, is much more than overbalanced by the diminished output of the machine which corresponds with the slow cutting speed. So little, however, is the effect of the duration of the cut upon the cutting speed generally understood that probably not one machinist in a thousand realizes that there exist clearly defined laws as to the effect of the duration of the cut on the cutting speed. It is also safe to say that for the purpose of avoiding frequent grinding it is the almost universal practice in machine shops to run tools at cutting speeds which are entirely too slow for maximum economy, when all of the elements bearing upon this subject are properly considered. And indeed this and the various other laws together present a problem which is so complicated that no mechanic or even mathematician can quickly and correctly solve it without the use of slide rules. As stated in paragraphs 113 to 119 even with the slide rules but comparatively small gain will be made unless the older type of management has been superseded by the system of task management with its accompanying aids in the form of functional foremanship, written instructions and its various safeguards.

695 Several series of careful experiments have been made by us at different times to investigate the precise effect of the duration of cut upon the cutting speed. The first of these was made in 1883 at the Midvale Steel Works, with carbon tempered tools, both when the tools were run dry and when they were run under a heavy stream of water. The summary of the results of these experiments will be described in paragraphs 706 and 707.

EFFECT UPON CUTTING SPEED OF DURATION OF CUT, MODERN HIGH SPEED TOOLS BEING USED

696 The only experiments which are of practical interest in this field are those made with modern high speed tools.

697 On Folder 15, Table 103, is given a summary of one set of experiments in which the important details of each tool trial are entered. Underneath each set of trials we give our conclusion as to the correct cutting speed corresponding to the given duration of cut. In these experiments, tools made of the following chemical composition were used:

Tungsten	8.50 per cent
Chromium	2.00 per cent

Carbon..... 1.85 per cent
Manganese..... 0.15 per cent
Silicon..... 0.15 per cent

698 In the test made upon our standard tools, the shapes indicated in Folder 5, Fig. 23, were used, ground to the following angles:

Clearance, 6 degrees
Back slope, 8 degrees
Side slope, 14 degrees

699 Each tool had previously been standardized upon a forging of as uniform steel as we could obtain, so as to prove all of the tools to be approximately uniform in their cutting speeds. A test piece of annealed steel about 24 inches in diameter and 10 feet long, having approximately the following chemical composition and the following physical test was used for making the trial.

CHEMICAL COMPOSITION OF FORGING		PHYSICAL PROPERTIES OF FORGING	
C	0.34	Tensile Strength	71300
Mn	0.60	Elastic Limit	32590
Si	0.183	Per Cent Extension	29.00
P	0.035	Per Cent Contraction	49.57
Su	0.032		

700 On Folder 15, Fig. 104, are plotted the summarized values given on Folder 15, Table 103, and a curve approximating these values is drawn on the diagrams. This curve is represented by the following formulæ:

$$V = \frac{90}{T^{\frac{1}{8}}} \text{ in which}$$

V = speed of the tool in feet per minute;
T = length of time tool must last without grinding.

701 The data expressed in this formula and by this curve may be given also in the following simple form. If we know the proper cutting speed for a tool which is to last 20 minutes, and we wish to find the cutting speed for a tool to last 40 minutes, multiply the 20-minute cutting speed by 0.92, and if we have the proper cutting speed for a tool to last 20 minutes and we wish to find the proper cutting speed for a tool to last 80 minutes, multiply the 20-minute cutting speed by 0.84. (See Folder 15, Table 105)

702 A glance at these figures will show the material gain in cutting speed which can be made by grinding tools every 20 minutes, say, instead of grinding them every 80 minutes.

703 It will be noted that in this table and formula we have included cuts of as short duration as 10 minutes. It is proper, however, to

call attention to the fact that the duration of 20 minutes is the shortest running time from which it is safe to draw any correct scientific conclusions from tests in the art of cutting metals. The reasons for this statement will be found in paragraphs 175 to 182, under the heading of "The nature of wear on tools depends upon whether it has been chiefly caused by heat," and in paragraphs 183–4 under the heading of "Reason for adopting the standard test period of 20 minutes."

704 There are certain classes of experiments, however, in which it is of great advantage to have even an approximate idea of the relation between the cutting speed of a tool which gives out in 10 minutes and that of tools which will last through a longer period; and it is for this reason that we have included the 101-minute period in our law; although we wish it distinctly understood that the same value does not attach to the 10-minute figures as to those corresponding to 20 minutes duration and upward.

705 We have made a number of experiments upon the effect of the duration of cut on cutting speed with different qualities of steel, and find that approximately the same relation exists between the duration of cut and cutting speed for steels of different degrees of hardness. This statement, however, does not apply to cast iron. See paragraph 709.

EFFECT UPON CUTTING SPEED OF DURATION OF CUT, CARBON TEMPERED TOOLS BEING USED

706 On Folder 15, Table 107, and on Folder 15, Fig. 106, are given the results of a similar experiment tried with carbon tempered tools. The steel which was cut was in this case a large locomotive tire. A practical rule resulting from these experiments is:

707 If we know the proper cutting speed for a tool which is to last 20 minutes, and we wish to find the cutting speed for a tool to last 40 minutes, multiply the 20-minute cutting speed by 0.87 or divide it by 1.15. And if we have the proper cutting speed to last 20 minutes and we wish to find the cutting speed for a tool to last 80 minutes, multiply the 20-minute cutting speed by 0.76 or divide it by 1.32.

EFFECT UPON CUTTING SPEED OF DURATION OF CUT, WITH MODERN HIGH SPEED TOOLS AND CARBON TOOLS COMPARED

708 A comparison of the following figures will show that the high speed tools fall off less in their cutting speed than the carbon tools, when they are run for a long time, since with tempered tools an 80-minute cut is 24 per cent slower than a 20-minute cut, while with

the modern high speed tools an 80-minute cut is only 16 per cent slower. The following table shows the increased durability of the new high speed steels even when they are run at their proper cutting speeds.

	DURATION OF CUT		AN 80-MINUTE CUT IS FOLLOWING PER CENT SLOWER THAN A 20-MINUTE CUT
HIGH SPEED TOOLS, CUTTING SPEED	20 MINUTES	80 MINUTES	
	99 ft. per minute	83 ft. per minute	16 per cent
CARBON TEMPERED TOOLS, CUTTING SPEED	16 ft. per minute	12 ft. per minute	24 per cent

EFFECT UPON CUTTING SPEED OF DURATION OF CUT IN CUTTING CAST IRON

709 We have made several attempts to accurately determine the law governing the effect of the duration of cut upon cutting speeds when tools were used upon cast iron. These experiments have up to date, however, been uniformly unsuccessful, because we have failed to obtain a sufficiently large and uniform body of cast iron to enable us to make the number of tests required for an accurate determination of the law. In general, however, it may be said, that those tests which we have made indicate that tools are even more enduring in cutting cast iron than in cutting steel; *i. e.*, that there is a smaller percentage of falling off in cutting speed between a 20- and an 80-minute cut in cast iron than there is with the corresponding cuts in steel.

HOW LONG SHOULD A TOOL BE RUN WITHOUT REGRINDING?

710 Perhaps the most important practical decision to be made after studying the laws of the effect of the duration of cut upon the cutting speed, all things considered, is: what is the most economical length of time for running each sized tool before regrinding it?

711 It is clear that we have on the one hand the main fact that the more often we are willing to grind the tool the higher the cutting speed at which the tool can be run, and therefore the larger the amount of work which will be turned out by the machine. On the other hand, there are four opposing considerations all of which tend toward a greater expense the more frequently the tools are ground. These considerations are:

712 (A) The time required to remove the worn-out tool from the tool-post; get another sharp tool; set and clamp it into the tool-post; and again start the roughing cut to exactly the proper size. For exact figures see, Folder 15, Table 108.

713 (B) The time of the tool grinder and the grinding machine and the wear on the emery wheel each time a tool is ground, which can be expressed in terms of the time of the lathe hand and his lathe time. For exact figures see, Folder 15, Fig. 108.

714 (C) The cost of the smith's and helper's wages, and fire, blast, etc., in the smith shop, for dressing a tool; which cost should be divided by the total number of times the tool is ground before it requires redressing. And this fraction of the dressing cost can then be expressed also in terms of the time of the lathe hand and his lathe. For exact figures see, Folder 15, Fig. 108.

715 (D) The cost of the tool steel which is lost every time a tool is redressed. This cost should also be divided by the total number of times the tool is ground, and expressed in terms of the time of the lathe hand and lathe. For exact figures see, Folder 15, Fig. 108.

716 This problem has been put into definite mathematical form and solved by us as follows: Let us assume that the cost of the grinder's wages plus the cost of the grinding machine is the same per hour or minute as the cost of the lathe in which the work is being done plus the wages of the lathe hand for lathes using certain sized tools; and that for lathes using larger sized tools the grinding machine cost is proportionally smaller, while for lathes using smaller tools the grinding machine cost is proportionally larger. Also, in a similar way the cost of the smith and his helper and of the fuel are expressed in terms of the time of the lathe hand and his machine, as stated above. This enables us then to arrive at the following mathematical solution of the problem.

717 Folder 15, Table 108, we have given the time required to dress and grind the various sized tools, and also the time required to place them in the machine, remove them from the machine, and start the cut. These data have been compiled from accurate observations made in each case by a competent observer with a stop watch, while the grinder, the lathe hand, and the smith were working at their proper normal speeds. In the same table we have also given the average number of times that each of the sizes of our standard tools can be reground before requiring to be redressed. The cost of the tool steel used each time a tool is dressed is also found in the same table.

THE MOST ECONOMICAL DURATION OF THE CUT IN CUTTING STEEL

718 In paragraph 700 will be found the following formula for the relation between the cutting speed V and the length of time T that the tool will last before requiring to be reground.

$$\frac{V}{V_o} = \left(\frac{T_o}{T}\right)^{\frac{1}{8}} \qquad [A]$$

Solving this for V we get:

$$V = V_o \frac{T_o^{\frac{1}{8}}}{T^{\frac{1}{8}}} = \frac{\text{Constant}}{T^{\frac{1}{8}}} = \text{Constant} \times T^{-\frac{1}{8}} \qquad [B]$$

for any given hardness of metal and efficiency of tool.

719 Let t = the sum of the four periods of time $A + B + C + D$ described in paragraphs **716** and **717**. Let us then look upon the time t as if it were all time lost or necessarily wasted by the lathe hand and his machine after he has run his tool continuously for T minutes; or, in other words, let us assume that, during a period of $T + t$ minutes the tool will be cutting for T minutes and then give out, and that the machine, as a consequence, will be laid idle during the remaining t minutes.

720 Now, the cutting speed of the tool being V, the quantity or weight of metal W removed (in the total time $T + t$) must be directly proportional to the product VT; that is,

$$W = \text{Constant} \times VT \qquad [C]$$

721 Let r = the average rate at which the metal is removed during the whole period $T + t$, then we have

$$r = \frac{W}{T + t} = \text{Constant} \times \frac{VT}{T + t} \qquad [D]$$

722 But we have seen, formula (B), that $V = \text{Constant} \times T^{-\frac{1}{8}}$ which substituted in formula [D] gives

$$r = \text{Constant} \times \frac{\text{Constant} \times T^{-\frac{1}{8}} \times T}{T + t} = \text{Constant} \times \frac{T^{\frac{7}{8}}}{T + t} \qquad [E]$$

723 Let n = the number of times t is contained in T then we have

$$T = nt \qquad [F]$$

and substituting [F] in [E], we have

$$r = \text{Constant} \times \frac{(nt)^{\frac{7}{8}}}{nt + t} = \text{Constant} \times \frac{n^{\frac{7}{8}}\, t^{\frac{7}{8}}}{(n+1)\, t} = \frac{\text{Constant}}{t^{\frac{1}{8}}} \times \frac{n^{\frac{7}{8}}}{n+1}. \qquad [G]$$

724 However, for any given tool, t is also a constant, and we finally get from [G]

$$r = C \times \frac{n^{\frac{7}{8}}}{n + 1} \qquad [H]$$

in which C is a complex constant.

725 Assuming successive values for n from o up, we get the following corresponding values for the expression $\frac{n^{\frac{7}{8}}}{n+1}$, to which the corresponding values of the rate r are proportional.

n	0	1	2	3	4	5	6	7	8
$\frac{n^{\frac{7}{8}}}{n+1}$	0	0.5000	0.6119	0.6538	0.6728	0.6815	0.6852	0.6862	0.6854
n	9	10	12	15	20	25	30	35	40
$\frac{n^{\frac{7}{8}}}{n+1}$	0.6839	0.6817	0.6766	0.6683	0.6549	0.6432	0.6326	0.6234	0.6152

726 We thus see that the rate r increases very rapidly with n, to begin with; reaches a maximum[1] for $n = 7$, is not far from this maximum for n as low as 5, and remains close to this maximum as far as $n = 10$, and even beyond this falls off at a very slow rate only.

727 If we put the value of the maximum rate ($r_m = C \times 0.6862$) equal to 100, we get the following table of the other rates corresponding to the various values of n in per cent of this maximum rate (for $n = 7$), by multiplying $\frac{100}{0.6862}$ by the various values of $\frac{n^{\frac{7}{8}}}{n+1}$.

n	0	1	2	3	4	5	6	7	8
Per cent of Max.	0	72.9	89.1	95.3	98.1	99.3	99.9	100	99.9
n	9	10	12	15	20	25	30	35	40
Per cent of Max.	99.7	99.4	98.6	97.4	95.5	93.7	92.2	90.8	89.7

728 This table of rates of removing the metal in per cent of the maximum rate is graphically represented by the diagram on Folder 15, Fig. 100.

[1]That this rate is a maximum for $n = 7$, and not merely approximately so (which is all that can be fully asserted from the inspection of the table), is readily shown by differentiating the function, $r = C \times \frac{n^{\frac{7}{8}}}{n+1}$, and finding that value of n for which $\frac{dr}{dn} = 0$; thus

$$dr = C\frac{(n+1)\,dn^{\frac{7}{8}} - n^{\frac{7}{8}}\,d\,(n+1)}{(n+1)^2}$$

$$= C\frac{(n+1)\,\frac{7}{8}n^{-\frac{1}{8}}.dn - n^{\frac{7}{8}}.dn}{(n+1)^2},$$

and $$\frac{dr}{dn} = C \times \frac{7(n+1) - 8n}{8(n+1)^2 n^{\frac{1}{8}}} = \frac{C}{8(n+1)^2 n^{\frac{1}{8}}}(7-n),$$

which becomes 0 for $n = 7$.

EFFECT OF FEED AND DEPTH OF CUT ON CUTTING SPEED

THE EFFECT OF VARYING THE FEED AND THE DEPTH OF THE CUT UPON THE CUTTING SPEED

The following are the principal conclusions arrived at on this subject:

729 (A) With any given depth of cut metal can be removed faster, *i. e.*, more work can be done, by using the combination of a coarse feed with its accompanying slower speed than by using a fine feed with its accompanying higher speed. (See paragraphs 743 to 751)

730 For example, by referring to any of the sets of experiments in cutting steel, described in paragraphs 743 to 772, it will be noted that if with a combination of $\frac{3}{16}$ inch depth of cut and $\frac{1}{64}$ inch feed, the hardness of the metal were of such a quality, for instance, that just 100 pounds of chips would be cut off in an hour by using the same tool on the same forging at its proper cutting speed corresponding to a feed of $\frac{1}{8}$ inch, the metal would then be removed at the rate of 250 pounds per hour. In most cases it is not practicable for the operator to take the coarsest feeds, owing either to the lack of pulling power of the machine or the elasticity of the work. Therefore, the above rule is only of course a broad general statement.

731 (B) The cutting speed is affected more by the thickness of the shaving than by the depth of the cut. (See paragraphs 761 to 763) A change in the thickness of the shaving has about three times as much effect on the cutting speed as a similar or proportional change in the depth of the cut has upon the cutting speed. Dividing the thickness of the shaving by 3 increases the cutting speed 1.8 times, while dividing the length that the shaving bears on the cutting edge by 3 increases the cutting speed 1.27 times. (See paragraphs 303 to 306)

732 (C) Expressed in mathematical terms, the cutting speed varies with our standard round nosed tool approximately in inverse proportion to the square root of the thickness of the shaving or of the feed; *i. e.*, S varies with $\sqrt{F}$ approximately. (See the various formulæ from paragraphs 770 to 787)

733 (D) With the best modern high speed tools, varying the feed and the depth of the cut causes the cutting speed to vary in practically the same ratio whether soft or hard metals are being cut. (See paragraphs 1062 and 815 to 828)

734 (E) The same general formula expresses the laws for the effect of depth of cut and feed upon the speed, the constants only

requiring to be changed. (See paragraphs 769 to 770) This is a matter of very great importance, as it enables us to use a single slide rule as a means of finding the proper combination of speed and depth of cut and feed for all qualities of metal which may be cut. (See paragraph 772)

736 (F) The same general type of formula expresses the laws governing the effect of the feed and depth of cut upon the cutting speed when using our different sized standard tools. This is also fortunate as it simplifies mathematical work in the final solution of the speed problem. (See paragraph 772)

IMPORTANCE OF THE STUDY OF EFFECT OF FEED AND DEPTH OF CUT UPON CUTTING SPEED AND THE DIFFICULTIES ATTENDING THESE EXPERIMENTS

737 A study of the effect of the feed and depth of cut upon the cutting speed constitutes in our judgment the most important element in the art of cutting metals. As pointed out in the opening paragraphs of this paper, the three questions which must be answered each day in every machine shop by every machinist who is running a metal cutting machine, such as a lathe, planer, etc., are:

WHAT TOOL SHALL I USE?
WHAT CUTTING SPEED SHALL I USE?
WHAT FEED SHALL I USE?

738 Having already established in a shop standards for the shape and quality of the tools, there remain but two of these questions to be answered, namely, as to the cutting speed and the feed. And the decision as to the cutting speed will depend more upon the depth of cut and feed which are chosen than upon any other element.

739 Experiments upon these two elements can only be undertaken after practically all of the other elements in the art of cutting metals have been standardized. A standard quality of tool steel and its proper heat treatment must have been established. A standard curve for the cutting edge of the tools, with standard lip angles, back slope and side slope, must have been established. The effect of the quality of the metal which is to be cut upon the pressure on the tool and of the pressure on the tool upon the pulling or driving power of the machine must be known before it is possible to decide upon the depth of cut and feed.

740 The depth of cut and feed, then, are of necessity almost the last elements to be experimented upon, and with the exception of determining the combination of the best tool steel and its proper heat

treatment, they constitute the two elements to which we have given the largest amount of time and study. We have undertaken many sets of experiments upon this subject since 1881 when we first began its investigation, and as discussed in paragraph 213 the accurate determination of these laws is rendered especially difficult owing to the necessity for making such a large number of experiments in cutting pieces of test metal which are uniform in quality. We have found it difficult to obtain large enough masses of uniform metal to accurately determine these laws, and each improvement in the quality of the tool steel which gives higher cutting speeds calls for larger and larger masses of uniform test metal, thus greatly increasing the difficulty and expense of these experiments.

741 Moreover, each change in almost any one of our important standards involves in the end a more or less elaborate investigation as to what modification the new standard has made in the effect that a change of feed or depth of cut has upon the cutting speed. Time after time the absolutely necessary changes in standards have forced us to reinvestigate the effect of feed and depth of cut upon cutting speed; and viewed from the point of expense alone, such an investigation is truly a serious undertaking. It is a matter of doubt to the writer whether with our accumulated experience it would be possible even now for us to make a consistent series of experiments either upon steel or cast iron with these two elements at a smaller cost than $5000.

742 All of these facts emphasize the desirability for the greatest care and consideration in adopting shop standards, and indicate the importance of not changing shop standards when once adopted except from imperative necessity.

PRACTICAL TABLES GIVING CUTTING SPEEDS CORRESPONDING TO DIFFERENT DEPTHS OF CUT AND THICKNESS OF FEED ON HARD, MEDIUM AND SOFT STEEL AND ON HARD, MEDIUM AND SOFT CAST IRON, WHEN BEST MODERN HIGH SPEED TOOLS OF OUR STANDARD SHAPES ARE USED

743 Before starting to discuss the experiments upon this subject and the formulæ which we have developed to represent the conclusions drawn from them we give the following:

744 Folder 24, Figs. 143–154, are practical working tables which will be found useful by machine shop foremen and machinists as a general guide to determining what cutting speed to use under several of the usual or typical conditions met with in ordinary machine shop practice. The cutting speeds given in these tables are based upon

the use of our standard tools, shown on Folder 5, Figs. 24 and 28, for cutting hard steel and cast iron, and those shown in Folder 5, Figs. 24 and 20b for cutting medium and soft steel. In making these tables we also assumed the use of the best quality of high speed tool as represented by tool No. 1 (Folder 20, Table 138), treated in the best manner, as described by us in paragraphs 979 to 994. The tables were also based upon cutting three different qualities of steel, having the following chemical and physical properties, and the following cutting speeds when cut with our standard $\frac{7}{8}$ inch tool, $\frac{3}{16} \times \frac{1}{16}$ cut, for standard 20-minute cut.

745 HARD STEEL Cutting speed, 45 ft. per minute; Class No. $21\frac{1}{4}$, (such for instance as is used in a hard locomotive tire)

Carbon	0.64 per cent
Manganese	0.70 per cent
Silicon	0.21 per cent
Phosphorus	0.044 per cent
Tensile strength	118,500 lbs.
Elastic limit	70,000 lbs.
Percentage of stretch	14

746 MEDIUM STEEL Cutting speed, 99 ft. per minute; Class No. 13.

Carbon	0.34 per cent
Manganese	0.60 per cent
Silicon	0.183 per cent
Sulphur	0.032 per cent
Phosphorus	0.035 per cent
Annealing heat,	1275 degrees Fahr.
Tensile strength	72,830 lbs.
Elastic limit	34,630 lbs.
Per cent of stretch	30
Per cent of contraction	48.73

747 SOFT STEEL Cutting speed, 108 ft. per minute; Class No. $5\frac{3}{4}$.

Carbon	0.22 per cent
Manganese	0.42 per cent
Silicon	0.07 per cent
Sulphur	0.025 per cent
Phosphorus	0.022 per cent
Annealing heat,	1200 degrees Fahr.
Tensile strength	56,250 lbs.
Elastic limit	26,590 lbs.
Per cent of stretch	35.50
Per cent of contraction	56.26

751 The tables made out for cutting cast iron are based upon three qualities of cast iron which we have found representative of hard, medium and soft cast iron as ordinarily found in the average machine shop in this country. In each shop, however, accurate experiments should be made to determine the average cutting speeds of the cast iron actually used. It should be noted also that the cutting speeds given in these tables are those which should be used in order to have the cutting tool last about the length of time stated in Folder 15, Table 108, which we recommend as the most economical time for allowing a tool to run without regrinding.

752 It is of course evident that where slide rules are used in a shop far more accurate results and a larger output can be obtained than with the use of tables similar to those illustrated. However, these tables may be of some interest and we hope also of practical use.

753 This section of the paper is entitled "The Effect of Varying the Feed and the Depth of the Cut upon the Cutting Speed." It should be noted that a change in feed produces a change in the thickness of the chip which is cut by the tool, and that it is the actual thickness of the chip as it crosses the line of the cutting edge of the tool which causes or produces the change in cutting speed. The thinner the chip or shaving the higher the cutting speed, and the thicker the chip the slower the cutting speed. (See paragraphs 292 to 297, explaining the causes for wear on tools and the effect of the pressure of the chip upon the tool.)

754 Now the actual thickness of the chip is dependent not only upon the coarseness of the feed that is, the advance of the tool for each revolution of the work, but also:

a upon the shape of the cutting edge of the tool, and

b upon the position of the tool in the tool post; *i. e.*, the angle at which the cutting edge of the tool is set with relation to the center line of the work.

758 In paragraphs 307 to 311 we have pointed out, and in Folder 16, Fig. 112, we illustrate, the fact that with all curved line cutting edges the chip must necessarily vary in thickness at all points, and that a straight line is the only shape for the cutting edge of a tool in which the thickness of the shaving is uniform throughout its length.

759 The experiments on the effect of feed and depth of cut which are of the greatest practical interest, and the results of which are required for everyday use refer to our standard round nosed tools; but, as just explained, with our standard round nosed tools the actual thickness of the shaving is affected by a change in the depth of the cut as well as by a change in the feed, therefore any investigation

made with these standard tools must necessarily include at the same time both the effect of a change in the feed and in the depth of cut upon the cutting speed.

760 With but little thought, therefore, it becomes evident that for the primary or more fundamental investigation as to the effect which the thickness of the chip or shaving has upon the cutting speed, it is desirable to experiment first upon shavings which are uniform in thickness throughout their whole length, and therefore we first describe our experiments with different thicknesses of shaving uniform throughout their length.

EXPERIMENTS SHOWING EFFECT UPON CUTTING SPEED OF VARYING THE THICKNESS OF THE SHAVING, A TOOL WITH STRAIGHT EDGE BEING USED, REMOVING A SHAVING IN ALL CASES EXACTLY ONE INCH LONG

761 In the early part of this paper it was found necessary to describe (paragraphs 292 to 297) our experiments with tools having a straight cutting edge and a uniform thickness of shaving throughout the length of the cutting edge. In order to avoid repetition, therefore, the reader is requested to read these paragraphs. However, the description there given of the experiments is not complete, and we supplement it here as follows:

762 The cutting speeds obtained in these experiments are laid out on two different types of diagrams. In Folder 16, Fig. 114, they are shown upon ordinary cross-section paper and in Folder 16, Fig. 115, upon logarithmic paper; and a comparison of the two sets of diagrams indicates clearly the great advantage of the logarithmic lay-out over that on ordinary cross-section paper; since, as will be noted, the spots or points indicating the cutting speeds upon the logarithmic paper lie almost in straight lines, and this fact helps greatly in finding the empirical formulæ representing the curves. It will be noted also that all the formulæ representing the laws as investigated by us are of the same general type. With this type of formulæ it is possible to express a great variety of laws, and, as will be explained in paragraph 1195, this type of formula was adopted because it was capable of being expressed entirely in logarithmic terms, and for this reason all of our laws can be incorporated in a slide rule. However, in most cases in describing the curves which represent the laws deduced we give both the logarithmic and the cross-section lay-out.

763 In studying these diagrams it will be remembered, as before indicated, that each of the figures given in our summary table and each of the spots or points given on the diagram is the result of many

experiments made with carefully standardized tools upon metal as uniform in quality as we were able to obtain.

764 As we have before explained, paragraph 28, owing to the enormous number of experiments made (between 30,000 and 50,000) it would be ridiculous for us to burden any published paper with even the principal details of our experiments. Therefore, it has become necessary for us to show by the sample sheets as indicated in the daily record sheet, Folder 11, Fig. 77, and the general summary sheets, Folder 8, Fig. 45, and Folder 11, Figs. 75, 76, the manner in which we originally recorded the results of our experiments and afterward collected them in groups, and finally drew our conclusions as to the results of each group of experiments. The points or spots, however, which are indicated upon our diagrams and which are given in our tables are in most cases arrived at by carefully plotting the final summary of several sets of similar experiments upon the same sheet of logarithmic paper; and as these experiments were made at different times and upon different pieces of test metal and with different tools, the general conclusions arrived at by us from considering together several sets of experiments instead of any one single set, in our judgment, have enabled us to approximate closely to the true laws governing this art.

EXPERIMENTS SHOWING THE EFFECT OF CUTTING SPEED OF VARYING THE DEPTH OF THE CUT, A TOOL WITH STRAIGHT EDGE BEING USED, REMOVING IN ALL CASES A SHAVING 0.03 INCH THICK

765 Having shown the effect upon the cutting speed of varying the thickness of the shaving it is desirable to show the effect of changing the depth of the cut upon the cutting speed; and this again fundamentally can best be accomplished by a study of tools with straight line cutting edges. For a description of these experiments we again refer our readers to paragraph 299. In further discussion of these experiments we would call attention to the logarithmic and cross-section paper diagrams in Folder 17, Figs. 118, 119, on which these experiments are plotted.

766 The experiments above described with straight edge tools both upon varying the thickness of the chip and varying the depth of the cut were made in 1886 with carbon tools, a heavy stream of water being used to cool the tool. As these experiments were made for the purpose of obtaining certain theoretical information rather than for practical everyday use in making our slide rules, they have not been repeated since that time. It is evident, therefore, that it is of

very great importance to repeat these experiments using the best modern high speed tools and thus bringing this branch of our work up to date. A series of experiments of this sort was planned by us for this summer, but owing to lack of time it has not been carried far enough to record in this paper.

EFFECT OF VARYING THE THICKNESS OF THE FEED AND DEPTH OF CUT UPON THE CUTTING SPEED WHEN OUR STANDARD ROUND NOSED TOOLS ARE USED IN CUTTING STEEL

767 In Part 1 of this paper we have called attention to the fact that the difficulty of obtaining mathematical expressions or formulæ which accurately correspond to the data obtained in our experiments has been almost as great as that of making the experiments themselves, and we may say that through a very considerable portion of the past 26 years we have worked at the mathematical side of this problem. The writer believes that he is well within the limit in stating that during this time we have tried and developed hundreds of formulæ in our endeavor to give accurate mathematical expression to the facts. It may, therefore, be a matter of interest to briefly indicate the logic back of the type of formula finally adopted.

768 It will be noted by referring to Folder 5, Figs. 21a, 21b, that all of our standard tools are similar in their general outline. They consist of an arc of a circle, whose radius is r, at their extreme noses, supplemented by another arc of a circle giving the remainder of the cutting edge of the tool; and in the general similarity existing between these tools it will be observed that the radius of the curve at the extreme nose of the tool may he said to be the controlling factor or element.

769 We have several times pointed out the fact that a curved cutting edge in a tool cuts a shaving varying in its thickness at all points, and it is evident that the rate at which this shaving grows thicker as the cutting edge recedes from the extreme point of the nose bears a certain relation to the radius r, above referred to. This will be seen by referring to the enlarged curves of our standard tools on Folder 17, Fig. 120. Generally speaking, the shaving growsthicker more rapidly the smaller the radius r of the curve, and since the thicker the shaving, the slower becomes the cutting speed, there is thus seen a general relation between this radius r and the cutting speed.

770 This relation is expressed in the following general formula in which

V =standard cutting speed in feet per minute. (For definition of standard cutting speed, see paragraph 140)

F = thickness of the feed in inches, *i. e.*, advance of the tool in inches for each revolution of the forging;

D = depth of cut in inches, *i. e.*, half of the amount by which the forging is reduced in diameter by the cut;

r = radius of nose of tool = one-half width of shank of tool in inches — $\frac{5}{32}$ inch, shown on Folder 5, Fig. 21a,

and in which the value of the constant depends both upon the hardness of the material to be cut and on the quality of the tool, in such a manner that the harder the material, the smaller this constant, and the better the tool the greater this constant:

$$V = \frac{\text{Constant}\left(1-\frac{8}{7(32r)}\right)^{*}}{F^{\frac{2}{3}} + \frac{2.12}{5+32r}\left(\frac{48}{32r}D\right)^{\frac{2}{1.5}} + 0.06\sqrt{32r} + \frac{0.8\,(32r)}{6\,(32r)+48D}} \qquad [A]$$

771 The reasons for the particular form of this general formula are so many and complexly interwoven that it would require pages of description to set them forth; and inasmuch as the whole formula is empirical our reasons are after all of minor interest.

772 We would, however, call special attention to the fact that the particular formulæ developed from our general formula fit in quite a remarkable way the actual data obtained in our experiments. This will be noted by examining the curves of the diagrams representing each formula in their relation to the spots or points on these diagrams representing the facts. Moreover, inasmuch as these experiments were made by different experimenters and at different times and upon different pieces of metal with different sets of tools, it adds very greatly to the probability of the general accuracy of our work that it has been possible to find a single general formula which fits so closely to all these practical results. It is perhaps, on the whole, the best possible evidence that the experiments have been accurately and conscientiously made, and proves beyond a doubt that general laws exist covering this whole field.

773 For the various tools up to and including $1\frac{1}{4}''$ to which we can apply this formula with reasonable accuracy, formula [A], paragraph 770, becomes:

*The expression $\left(1-\frac{8}{7(32r)}\right)$ in the numerator of the general formula [A] was arrived at by a comparison of the cutting speeds obtained by standardizing various sized tools on the same forging preparatory to using them in any one of the separate series of experiments subsequently made.

774 For $\frac{1}{2}''$ tool, for which $r = \frac{3}{32}''$,

$$V = \frac{\text{Constant} \times 0.87}{F^{0.665}\left(\frac{48}{3}D\right)^{0.2373 + \frac{2.4}{18+48D}}} \qquad [B]$$

775 For $\frac{5}{8}''$ tool, for which $r = \frac{5}{32}''$,

$$V = \frac{\text{Constant} \times 0.954}{F^{0.612}\left(\frac{48}{5}D\right)^{0.2675 + \frac{4}{30+48D}}} \qquad [C]$$

776 For $\frac{3}{4}''$ tool, for which $r = \frac{7}{32}''$,

$$V = \frac{\text{Constant} \times 0.977}{F^{0.5767}\left(\frac{48}{7}D\right)^{0.2921 + \frac{5.6}{42+48D}}} \qquad [D]$$

777 For $\frac{7}{8}''$ tool, for which $r = \frac{9}{32}''$,

$$V = \frac{\text{Constant} \times 0.986}{F^{0.5514}\left(\frac{48}{9}D\right)^{0.3133 + \frac{7.2}{54+48D}}} \qquad [E]$$

778 For $1''$ tool, for which $r = \frac{11}{32}''$,

$$V = \frac{\text{Constant} \times 0.991}{F^{0.5325}\left(\frac{48}{11}D\right)^{0.3323 + \frac{8.8}{66+48D}}} \qquad [F]$$

779 For $1\frac{1}{4}''$ tool, for which $r = \frac{15}{32}''$,

$$V = \frac{\text{Constant} \times 0.995}{F^{0.506}\left(\frac{48}{15}D\right)^{0.3657 + \frac{12}{90+48D}}} \qquad [G]$$

781 We will now proceed to describe some of the more prominent sets of experiments made by us with various sized tools, and which form the basis for the above given formulæ.

782 EXPERIMENTS WITH $\frac{7}{8}$ INCH STANDARD ROUND NOSED TOOL. (Shown in Folder 8, Fig. 45). On Folder 18, Table 129, will be found a sample summary sheet of one of our series of experiments made with our standard $\frac{7}{8}$ inch tool. In this table are recorded the important data connected with each experiment made with each individual tool. In this series of experiments we were, on the whole, successful in having a combination of uniform quality of metal to cut, unusual uniformity in the cutting tools, and also great care on the part of the experimenter; and it is seldom that all of these favorable conditions

are found in any one set of experiments. This table may, therefore, be said to represent one of the best series of experiments made by us.

783 The conclusions noted in this table will be found in the summary table, Folder 18, Table 129, and alongside of them are entered also the cutting speeds as figured by the formula given below. A comparison of the cutting speeds given by the formula in paragraph 777 with the proper constant covering this series of experiments as given in formula, paragraph 783, and those actually obtained in experiments will illustrate the degree of accuracy attained both in the experimental and mathematical work. Our conclusions are again plotted as points or spots upon ordinary cross-section paper in the diagram, Folder 18, Fig. 127, and again in a logarithmic lay-out in Folder 18, Fig. 128.

$$V = \frac{13.4}{F^{0.5514}\left(\frac{48}{9}D\right)^{0.3133 + \frac{7.2}{54 + 48D}}} \qquad [H]$$

784 The constant to be substituted in this formulæ for the best speed tool, No. 1 (on medium steel), as explained in paragraph 786, is 21.46.

785 The curves plotted in Folder 18, Fig. 127, and in Folder 18, Fig. 128, are a graphical expression of this formula. This set of experiments was made with tools of the chemical composition given in the printed matter beneath the diagrams. Further details regarding this tool and its cutting speed with relation to other high speed tools will be found in Folder 21, Table 139, opposite tool No. 27. The chemical composition and the physical properties of the metal experimented upon will also be found in the printing beneath the table and diagrams.

786 It will be noted that tools differing in their chemical composition were used for making the several sets of experiments described by us. In order to render the formula useful for the best modern high speed tools we therefore give, close to each formula, a constant which should be substituted in the formula if the best modern high speed tool had been used in making the particular experiment (we here refer to tool No. 1, Folder 20, Table 138); and also if the steel cut by this tool had been the medium steel referred to in Folder 20, Table 138, of the following chemical and physical properties:

Carbon	0.34
Manganese	0.54
Silicon	1.76
Phosphorus	0.037

Sulphur	0 .026
Tensile Strength	.70280 lbs.
Elastic Limit	.34630 lbs.
Percentage of stretch	.29
Percentage of contraction	44 .34

EXPERIMENTS WITH STANDARD 1 INCH TOOL (SHOWN IN FOLDER 5, FIG. 25a)

787 On Folder 18, Table 126, are recorded the results of experiments similar to those described in paragraphs 782 to 785, with $\frac{7}{8}$ inch tools, and in Folder 18, Fig. 125, is given the logarithmic lay-out of the results of this experiment. Formula, paragraph 787, below, which is the same as formula paragraph 778, with the proper constant, gives a mathematical expression corresponding to the results of this experiment. (For definition of the values given in this formula, see paragraph 770)

$$V = \frac{14.7}{F^{0.5325}\left(\frac{48}{11}D\right)^{0.3323 + \frac{8.8}{66 + 48D}}} \qquad [J]$$

788 The constant to be substituted in this formula for the best high speed tool No. 1, as explained in paragraph 786, is 21.56.

EXPERIMENT WITH STANDARD $\frac{1}{2}$ INCH TOOL, AS SHOWN IN FOLDER 5, FIG. 25d and 21a.

789 In Table 131, Folder 18, are recorded the results of experiments similar to those described in paragraphs 782 to 785 with $\frac{7}{8}$ inch tools, and in Folder 18, Fig. 130, is given the logarithmic lay-out of the results of these experiments. Formula, paragraph 789, below, which is the same as formula paragraph 774, with the proper constant, gives a mathematical expression corresponding to the results of these experiments. (For definition of the values given in this formula, see paragraph 770)

$$V = \frac{11.9}{F^{0.665}\left(\frac{48}{3}D\right)^{0.2373 + \frac{2.4}{18 + 48D}}} \qquad [K]$$

790 The constant to be substituted in this formula for the best high speed tool, No. 1, as explained in paragraph 786, is 19.

791 Similar experiments were made with our standard $\frac{5}{8}$ and $\frac{3}{4}$

inch tools, covering, however, not so wide a range of feeds and depths of cut, and the following formulæ represent with fair accuracy these tools when using the best high speed tool, No. 1, on medium steel, as explained in paragraph 786.

792 For $\frac{5}{8}$ inch standard tool, as shown in Folder 5, Fig. 25d, use formula (C), paragraph 775, except that the following will be substituted for the numerator:

20.77

793 For $\frac{3}{4}$ inch standard tool, as shown in Folder 5, Fig. 25b, use formula (D), paragraph 776, except that the following will be substituted for the numerator:

21.26

794 For $1\frac{1}{4}$ inch standard tool, as shown in Folder 5, Fig. 25e, use formula (G), paragraph 779, except that the following will be substituted for the numerator:

21.66

THE EFFECT OF VARYING THE THICKNESS OF FEED AND DEPTH OF CUT UPON CUTTING SPEED WHEN OUR STANDARD ROUND NOSED TOOLS ARE USED IN CUTTING CAST IRON

795 As heretofore explained, the difficulty in making a complete and consistent series of experiments upon cast iron is very great owing to the fact that masses of cast iron of uniform hardness and sufficiently large to make the many tool runs required can but rarely be made. After many trials we finally obtained three test pieces of cast iron, cast with a hollow core so as to give a comparatively thin section, the metal of which was proved in our experiments to be remarkably uniform.

796 These test pieces, however, contained only enough metal to make thorough experiments with a single sized tool.

797 As the law for cutting cast iron is only slightly different in character from that for cutting steel, we therefore assume that a similar relation exists between different sized tools in cutting cast iron and in cutting steel. The following formulæ are based upon this assumption and apply to tool No. 1 on medium cast iron.

798 For $\frac{1}{2}$ inch tool

$$V = \frac{68.3}{(20F)^{0.6383 - \frac{0.3}{1+100F}} \left(\frac{32}{3}D\right)^{0.1743 + \frac{0.27}{3+32D}}}$$

799 For $\frac{5}{8}$ inch tool

$$V = \frac{65.4}{(20F)^{0.5853 - \frac{0.3}{1+100F}} \left(\frac{32}{5}D\right)^{0.2182 + \frac{0.27}{3+32D}}}$$

800 For $\frac{3}{4}$ inch tool

$$V = \frac{62.0}{(20F)^{0.55 - \frac{0.3}{1+100F}} \left(\frac{32}{7}D\right)^{0.25 + \frac{0.27}{3+32D}}}$$

801 For $\frac{7}{8}$ inch tool

$$V = \frac{59.0}{(20F)^{0.5248 - \frac{0.3}{1+100F}} \left(\frac{32}{9}D\right)^{0.2757 + \frac{0.27}{3+32D}}}$$

802 For 1 inch tool

$$V = \frac{56.9}{(20F)^{0.5058 - \frac{0.3}{1+100F}} \left(\frac{32}{11}D\right)^{0.2978 + \frac{0.27}{3+32D}}}$$

803 For $1\frac{1}{4}$ inch tool

$$V = \frac{54.1}{(20F)^{0.4793 - \frac{0.3}{1+100F}} \left(\frac{32}{15}D\right)^{0.335 + \frac{0.27}{3+32D}}}$$

EXPERIMENT WITH A $\frac{3}{4}$ INCH STANDARD ROUND NOSED TOOL (AS SHOWN ON FOLDER 5, FIGS. 25b AND 21a)

804 Tools of the following chemical composition were used in this experiment:

Tungsten	14.71 per cent
Chromium	2.90 per cent
Carbon	0.70 per cent
Manganese	0.12 per cent
Silicon	0.196 per cent
Phosphorus	0.017 per cent
Sulphur	0.010 per cent

Their cutting speeds with relation to other high speed tools will be found by referring to tool No. 20, on Folder 20, Table 138.

805 On Folder 11, Table 76, we give the detail tool runs of one of our best sets of experiments made in cutting rather hard cast iron. The details of these experiments are given in order that a fair estimate may be formed as to the accuracy of the work. On Folder 19, Table 136, column 1, is given a summary of the results obtained in this series of experiments, and in adjoining columns will be found the corresponding figures as represented by the formula which we have developed and which expresses what we believe to be laws governing the effect of feed and depth of cut upon cutting speed in cutting this quality of cast iron.

806 On Folder 19, Fig. 134, are given two logarithmic plots of the same experiments. In one of these plots the feeds are given at the bottom and the depth of cut at the side, while in the other the depths of cut are given at the bottom and the feeds at the side. A study of these two diagrams side by side will indicate the effect both of varying the thickness of shaving and the depth of the cut, considered one with relation to the other.

807 On Folder 19, Fig. 135, we also show the same experiments plotted on ordinary cross-section paper. This again furnishes an illustration of the greater simplicity and adaptability of the logarithmic lay-out and particularly its advantage in developing formulæ which shall express the laws.

808 Unfortunately, the silicon was the only element accurately determined for the various bars of cast iron experimented upon by us at this time. The silicon of the bar in question was 1.10 per cent. The lines drawn upon the various diagrams just referred to represent the following formula:

$$V = \frac{54}{\left(20F\right)^{0.55 - \frac{0.3}{1+100F}} \left(\frac{32}{7}D\right)^{0.25 + \frac{0.27}{3+32D}}} \qquad [L]$$

809 It will be noted that the experiments above described upon the cast iron test piece containing 1.10 per cent of silicon include the following feeds:

0.0156″ 0.0316″ 0.0632″ 0.0127″

and the following depths of cut:

$\frac{3''}{32}$ $\frac{3''}{16}$ $\frac{3''}{8}$

This casting did not contain a sufficient quantity of metal to make tests with the combinations of depth of cut and feed which are needed

to more fully establish the law sought for. Therefore, two additional castings were made and experimented upon. It was our aim to have the same quality of cast iron in these castings as in the one containing 1.10 per cent of silicon. In this, however, we were not successful, as both of the other castings were considerably softer. One of these supplementary castings contained 1.12 per cent silicon, while the other contained 1.20 per cent silicon, and they varied considerably in hardness, as will be seen from their constants in the formulæ. On the test casting containing 1.12 per cent of silicon, experiments were made with cuts $\frac{5}{8}$ of an inch in depth and using feeds from 0.0156 to 0.0632 inch; and a sufficient number of experiments were made also with a depth of cut of $\frac{3}{16}$ of an inch to properly tie together these experiments and the former experiments made on the test piece containing 1.10 per cent of silicon; *i. e.*, to accurately determine the relative hardness of the two castings.

810 On Folder 19, Table 136, column 2, is given a summary of the the results obtained in this experiment and also alongside, the results as figured by the same formula, paragraph 808, for the experiments on the 1.10 per cent silicon bar, except that the constant instead of being 54 for this quality of cast iron is 66.7.

811 On Folder 19, Fig. 132, is also given a logarithmic lay-out of these experiments.

812 A third series of experiments was made upon the cast iron test piece containing 1.20 per cent of silicon. In this case most of the experiments were made with a $\frac{5}{8}$ inch depth of cut. However, a $\frac{3}{16}$ inch depth of cut was also used for tying these various sets of experiments together. A summary of the results of these experiments will be found on Folder 19, Table 136, column 3, with the results as figured by the formula in adjacent columns. The same formula (paragraph 808) was used for this set of experiments as for the experiments with a 1.10 per cent silicon test bar except that the constant in this case was 70.9 instead of 54, showing that this test piece was materially softer than the other.

813 By comparing the lines which represent each formula upon the three diagrams with the points or spots which indicate the actual cutting speeds obtained, it will be noted that, on the whole, the same formula fits very closely to the three sets of experiments, and attention is again called to the fact that while these experiments were made at different times and with different sets of tools, yet after several years we have been able to find a single mathematical expression which represents with a very considerable degree of accuracy the results obtained in all of these experiments.

814 This fact, in our judgment, adds very greatly to the value of the work, because if the experimental results had been such that no mathematical expression could be found which fitted them with accuracy, either one of two conclusions must be drawn: namely, that the conditions under which the experiments were made were such that accurate results could not be obtained, or else that the nature of the work in this whole field of experiments was such as to make it impossible to obtain truly scientific results. It is, therefore, a matter of the greatest gratification to us that it has been possible to represent these various experiments by exactly the same formula, excepting that the constants 54, 66.7 and 70.9 were required to represent the three different grades of hardness in the three qualities of cast iron.

THE INFLUENCE WHICH THE QUALITY OF METAL BEING CUT HAS UPON THE EFFECT OF VARYING THE FEED AND DEPTH OF CUT ON THE CUTTING SPEED

815 With high speed tools as originally developed by us the quality of the metal being cut had a very marked influence upon the laws governing the effect of varying the feed and the depth of cut upon the cutting speed. The following is an illustration of this effect.

816 With high speed steel of the chemical composition indicated for tools Nos. 26 and 27 (the original high speed tools developed by Messrs. Taylor and White), the quality of the tool steel was such that in cutting medium and hard steels, there was practically no increase in the cutting speed of the tool when feeds were used which were finer than $\frac{1}{16}$ of an inch; in other words, a feed of $\frac{1}{64}$ inch, $\frac{1}{32}$ inch and $\frac{1}{16}$ inch all had about the same cutting speed.

817 On the other hand, with tools of this quality in cutting a very soft forging, there was about the same proportionate gain in cutting speed on a cut taken with a $\frac{1}{32}$ inch feed over a cut taken with a $\frac{1}{16}$ inch feed, as there was with a cut taken with a $\frac{1}{16}$ inch feed over that taken with a $\frac{1}{8}$ inch feed.

818 As an illustration of this fact, we give below three cutting speeds, which were taken on a soft forging of the following chemical composition and physical properties:

Tensile strength	56,250 lbs.
Elastic limit	26,590 lbs.
Percentage of stretch	35.50
Percentage of contraction	56.26
Carbon	0.22 per cent
Manganese	0.42 per cent

Silicon .....0.07 per cent
Phosphorus.....0.022 per cent
Sulphur .....0.025 per cent

819 These experiments, which were very carefully made with standardized $\frac{7}{8}$ inch high speed tools (of the chemical composition, shown for tool No. 27, Folder 21, Table 129) on a forging of uniform metal gave the following cutting speeds:

For $\frac{3}{16}$ inch depth x $\frac{1}{16}$ inch feed .....120 ft. per minute
For $\frac{3}{16}$ inch depth x $\frac{1}{32}$ inch feed .....180 ft. per minute
For $\frac{3}{16}$ inch depth x $\frac{1}{64}$ inch feed .....260 ft. per minute

820 Thus it is seen that as the shaving or chip grows thinner, the cutting speed grows more rapid even in taking very fine feeds, whereas, as just explained above, with these same tools in cutting the medium or harder metals, no gain in cutting speed resulted from finer feeds than $\frac{1}{16}$ of an inch.

821 One of the great improvements of the latest high speed tools over the original high speed tools lies in the fact that a tool, for instance, of the chemical composition of tool No. 1, Folder 20, Table 138 (the best modern high speed tool), makes approximately the same gain in cutting speed when using very fine feeds in cutting even very hard steel as the original tools made only when cutting the very softest of steels. And this again is of truly great importance to the average machine shop, since in the average shop more cuts are taken with feeds finer than $\frac{1}{16}$ inch than with coarser feeds, and therefore a proportionate increase in cutting speed is made possible by the latest tool steels over fully one-half of the work in which no such gain was possible with the original tools.

822 As an illustration of this fact, we give the following experiments made by us during the summer and fall of 1906 with modern high speed tools in cutting very hard metals with fine feeds. The following are the details of one of these experiments made with composition of tool No. 2 on Folder 20, Table 138, in cutting the hard steel bar referred to in the same table having the following chemical composition and physical properties, our standard $\frac{7}{8}$ inch round nosed tool (see Folder 5, Fig. 24) being used in these experiments.

Tensile strength ..... { 91670 / 101860
Elastic limit ..... { 60090 / 53980
Percentage of stretch ..... { 7 / 5

Percentage of contraction	11.66 9.73
Carbon	1.00 per cent
Manganese	1.11 per cent
Silicon	0.305 per cent
Phosphorus	0.036 per cent
Sulphur	0.049 per cent

823 The following cutting speeds were obtained with our standard $\frac{7}{8}$ inch tool with a standard 20-minute cut:

a for $\frac{3}{16}$ inch depth x $\frac{1}{16}$ inch feed, cutting speed 41.4 ft. per minute.

b for $\frac{3}{16}$ inch depth x $\frac{1}{32}$ inch feed, cutting speed 58.2 ft. per minute.

c for $\frac{3}{16}$ inch depth x $\frac{1}{64}$ inch feed cutting speed 81.4 ft. per minute.

827 A comparison of the gain in cutting speed when taking fine feeds on this very hard forging will show that they are not far from proportional to the gain made in taking the fine feeds on very soft metal with the original high speed tools.

828 In paragraphs 1058 and 1063 we point out the fact that the reason why the latest high speed tools are able to make the same proportionate gain with fine feeds in cutting hard metals as when cutting soft metals is due to their possessing in a marked degree the two qualities of "red hardness" and "hardness." The original tools as developed by us were deficient as compared with the modern tools in the proper combination of red hardness and hardness.

829 We have made many experiments with tools larger than our standard $1\frac{1}{4}$ inch tool referred to in this paper, one of the most notable of these being a set with tools 2 inches square in the body having their cutting edges corresponding to our $1\frac{7}{8}$ inch standard. It has been impossible as yet, however, for us to obtain sufficiently conclusive results to enable us to state definitely the cutting speeds of these larger types of tool when taking greater depths of cut and coarser feeds than those already experimented with.

830 Accurate experiments of this nature are greatly needed to establish the proper cutting speeds for the few machine shops in which these very heavy cuts are taken. The expense of such experiments, however, is very great, and we have not yet had the opportunity of carrying them to their proper end. The formula which we give on this subject is, therefore, of very questionable value. We may state, however, that with our standard $1\frac{7}{8}$ inch round nosed tool with a cutting edge of the shape indicated in Folder

5, Fig. 21a, as high cutting speeds can be taken in all cases as those indicated in the small summary table, Folder 23, Table 142, when using the best modern high speed steel similar to that of No. 1 tool, Folder 20, Table 138.

831 It will be noted that we have in all cases stated the chemical composition of the tools with which from time to time our experiments as recorded have been made. We also give some of the details of experiments made with the best modern high speed tools for the purpose of accurately comparing the various cutting properties of these tools with the cutting properties of various types of tools formerly experimented with by us. As a result of these experiments we have been able to state what we believe to be approximately the proper cutting speeds for high speed tools under various conditions.

832 It must be remembered, however, that our comparatively few experiments with these tools did not cover the whole field. We attempted to make what we believed to be typical experiments, but we did not feel satisfied with either the extent or the thoroughness of this work. Therefore, it seems of great importance to more carefully verify the various laws obtained by us through direct experiments with the latest high speed tools. Among these for the purpose of establishing the fundamental basis upon which rests the effect of varying the feed and the depth of cut upon cutting speed, we think it of particular importance to make a series of experiments with tools having straight line cutting edges, both on the effect of the thickness of the chip upon the cutting speed and upon the effect of the depth of the cut upon the cutting speed. Such experiments should be similar to those made by us upon this subject with carbon tools, as described in paragraphs 292 to 299.

833 Attention is called to the necessity of determining accurately the effect of the thickness of the chip or a change in the feed, and also the effect of the depth of the cut upon the cutting speed when a heavy stream of water is used to cool the latest modern high speed tool.

TOOL STEEL AND ITS TREATMENT

CHEMICAL COMPOSITION AND HEAT TREATMENT OF TOOL STEELS

934 Among modern experiments upon the chemical composition and the heat treatment of tools with relation to their cutting speeds, the experiments made by the firm of Armstrong, Whitworth & Company, the celebrated ship, cannon and machine builders of England, would seem to rank in thoroughness next to those made by Mr. White and

the writer at the Bethlehem Steel Works. Or it would be more correct to say that no other published experiments have come to the writer's attention which appear to him to have been so carefully conducted.

935 In a paper entitled "The Development and Use of High-Speed Tool Steel" (published in the Journal of the Iron and Steel Institute, October, 1904), Mr. J. M. Gledhill, Managing Director of Armstrong, Whitworth & Company, has given a brief account of these experiments. The opening paragraphs of this paper present such a concise and interesting historical sketch of the development of tool steel and its treatment that the writer takes the liberty of quoting them as follows:

936 "It would doubtless have been felt by many but a few years back that there was little left to be said on the subject of crucible tool steel, and that something akin to finality had been arrived at in its manufacture and general treatment. Probably such feeling was justifiable when it is remembered that the making of steel in crucibles is by far the oldest method known, dating back from time immemorial, it being indeed impossible to accurately trace its origin and earliest development, but it seems certain that carbon steel was made and used thousands of years ago for cutting tools. Proof of this may be seen by the marvellous carvings and workings on the intensely hard stone work of the ancients, for it would be difficult to conceive by what means, other than with steel tools, such work could have been executed, and it is wonderful to contemplate that steel-cutting tools should have been used so long ago, whilst the principle of manufacturing them—that is, by fusion of iron and charcoal in crucibles—was then in a measure on the same lines as we work on at the present day. Archæologists have discovered that the Chinese made steel in crucibles long before the Christian era.

937 "Wootz" steel fabricated in India centuries ago was crucible steel, as was also the celebrated Damascus steel, produced at the forges of Toledo. Curiously, this latter steel furnishes yet another proof that there is nothing new under the sun, for it is recorded that Damascus steel contained certain percentages of tungsten, nickel, manganese, etc., some of the very elements, in fact, contained in the present modern high speed steel, so that a latent high speed steel may be said to have existed centuries ago, and all that was necessary to bring out its inherent powers would have been the heating of it in a paradoxical manner, so to speak; that is, to such a high degree of temperature as was long thought would impair or destroy the nature of such steel. When, therefore, we look back on the period for which

crucible steel has been known in the world's history, some may not unnaturally think that there has been time enough to have fully fathomed its mysteries leaving little more to be said on the subject. It is then all the more remarkable that a discovery, made but a few years back, and which has since revolutionized the treatment of crucible tool steel, should have remained so long a hidden secret.

938 "A very important advance was made thirty or forty years ago, when 'Mushet,' or self-hardening steel, was introduced. This was the valuable invention of Robert Mushet, who, after a long series of experiments, made whilst he was manager of the Titanic Steel Company; succeeded in producing a tungsten steel, and its introduction was a great advancement on the cutting powers of ordinary crucible steel, and for many years 'Mushet' steel held a foremost place amongst tool steels.

939 "It is now to America, however, that all honor must be given for the next great step in having 'set the pace' and led the way in the present remarkable advancement in tool steel, and the author would here like to record that the greatest credit is due to Messrs. Taylor and White, who at the Bethlehem Steel Works of America, initiated high-speed cutting, and at the exhibit of their firm in Paris some years back, what were then considered to be astonishing results in speeds of cutting steel were publicly demonstrated. Since then, still greater developments have been made by the author's firm in high-speed steels, and with increased experience in its manufacture, treatment, and application in our workshops, results in cutting powers far beyond expectation have been attained."

ORDINARY TOOL STEEL

940 For centuries steel weapons, knives, tools and implements used in cutting metals have been made from tool steel which in its chemical composition consists mainly of the two elements of iron and carbon--carbon to the extent of say from $\frac{3}{4}$ of 1 per cent to $1\frac{1}{2}$ per cent--and the rest of the steel consists practically of iron. In addition to these two elements, however, tool steel has contained in small quantities several other ingredients, among which manganese and silicon may be classified as useful elements; *i. e.*, elements which facilitate melting and forging, and which by their presence improve the properties of the steel in its finished state. In addition to these elements very small percentages of phosphorus, and sulphur, are always present. These latter may be described or classified as impurities. Phosphorus is particularly injurious, as it causes brittleness in the finished steel known as "cold shortness." Sulphur renders the steel

difficult to work while hot, and this is known as "red shortness." This tool steel which has been in use for centuries past, and which, broadly speaking, consists mainly of a combination of carbon and iron, is now known as "carbon tool steel" or "ordinary tool steel".

HARDENING

941 Tools and implements made from this steel, however, are entirely too soft as they come from the forge for almost all cutting purposes. In order to prepare them for cutting, they must be hardened, and this is done by heating them to temperatures in accordance with their carbon contents, varying between a dark and a bright cherry red, say, from 1350 degrees Fahr. (735 degrees Cent.) up to 1550 degrees Fahr. (845 degrees Cent.), and then by plunging them quickly into water or other suitable bath, cooling them very rapidly to a temperature not exceeding 392 degrees Fahr. (200 degrees Cent.), or preferably to the normal temperature of the air. This operation is called "hardening."

TEMPERING

942 When cooled suddenly in this way, implements and tools made from carbon tool steel are too brittle for most cutting purposes. This quality of brittleness is removed or modified by reheating to temperatures ranging bewteen 392 degrees Fahr. (200 degrees Cent.) and 600 degrees Fahr. (315 degrees Cent.). The higher the tool is reheated within these ranges of temperature, the softer it becomes, and this reheating for the purpose of partially softening and at the same time toughening the tool is the operation known as "tempering the tool."

ORDINARY TOOL STEEL

943 The two operations of hardening and tempering implements made from tool steel are by no means simple. They have been the subject of a vast amount of experimenting and investigation for many years and in themselves constitute whole trades.

944 The chief difficulties in hardening come from three causes:

945 (A) Each ordinary tool steel, depending upon its chemical composition, has a particular temperature at which a radical change takes place in the condition of the carbon which is contained in it. This temperature known as the "refining point," "critical point," or "point of recalescence" of the steel, will be briefly referred to later in the paper. In order to obtain the best results in hardening the steel should be uniformly heated to slightly above this critical point.

If heated below the critical point, it fails to harden when plunged into water. On the other hand, the higher the temperature to which it is heated above the critical point, the coarser will be the grain with increased weakness and brittleness after being plunged into water. This overheating of carbon steel tools to temperatures too high above the critical point has been in the past perhaps the most frequent cause of their failure. Hence the difficulty in judging the critical point for heating tools presents one of the most serious problems in hardening.

946 (B) The second difficulty lies in not heating the tools uniformly. A lack of uniformity in heating will produce irregularity in the degree to which the tool is hardened, some portions being much harder than others after quenching, and this sets up severe internal strains in the tool, frequently developing into water cracks.

947 (C) The third difficulty lies in properly cooling the tool in the water or quenching medium. Uneven or irregular cooling also produces severe internal strains often resulting in water cracks.

948 The correct tempering of tools presents also many difficulties. In most cases it is desirable to temper tools or implements so that the cutting portion shall remain exceedingly hard while the body is softened, and thereby made sufficiently tough to give it the required strength. This necessary combination of toughness and hardness calls for great skill and judgment in the reheating or softening operation known as "tempering."

949 One of the greatest advantages of modern high-speed tools over the carbon tools lies in the fact that they require far less knowledge and skill in their heat treatment than was demanded by the carbon tools. This will be indicated later in the paper.

MUSHET OR SELF-HARDENING STEEL

950 Some time between 1860 and 1870, Robert Mushet of the Titanic Steel Company in England made the discovery that if a considerable amount of tungsten was added to tool steel in combination with a larger percentage of manganese than had been before used, the presence of these two elements with carbon in the steel produced the curious effect of causing the tool to be almost as hard when cooled slowly in air from a forging heat as carbon tools when cooled in water. Because of this peculiar property, the Mushet tools were called in England self-hardening tools and later in this country air-hardening tools.

951 The chemical composition of the Mushet tools as analysed by us in the early part of 1905 is given in Table M and paragraph 952.

FOUR EPOCHS IN HISTORY OF STEEL TOOLS. (1) CARBON TOOL STEEL ERA; (2) SELF-HARDENING STEEL ERA; (3) DISCOVERY OF HIGH SPEED TOOLS; (4) MODERN HIGH SPEED TOOLS; WITH ANALYSES OF TOOLS OF THESE ERAS

952 We give below the chemical analyses of four tools which are typical of the various steps or eras in the development of metal cutting tools:

MAKE OF STEEL	TUNGSTEN PER CENT	CHROMIUM PER CENT	CARBON PER CENT	MANGANESE PER CENT	VANADIUM PER CENT	SILICON PER CENT	PHOSPHORUS PER CENT	SULPHUR PER CENT	SPEED PER MINUTE IN FEET CUTTING MEDIUM STEEL
Jessop		0.207	1.047	0.189		0.206	0.017	0.017	16
Mushet self-hardening	5.441	0.398	0.15	1.578		1.044			26
Original Taylor-White	8.00	3.80	1.85	0.30		0.15	0.025	0.030	58 to 61
Best modern high speed 1906	18.91	5.47	0.67	0.11	0.29	0.043			99

953 The first of these is the analysis of perhaps the most noted brand of ordinary carbon steel, that made by Messrs. Jessop & Sons of England, which is typical of the era of carbon tools. The second is the analysis of the old fashioned Mushet self-hardening steel as experimented with by us in 1894-95—typical of the era of self-hardening tools. The third is the analysis of the steel recommended by us in our Patent No. 668270 of February 19, 1901, as being, on the whole, the best at the time when modern high speed tools were invented by Mr. White and the writer, marking the beginning of "high speed" or "red hardened" tools. The fourth is the analysis of the best high speed tool, so far as we know, which has been developed up to the end of the summer of 1906.

954 For many years the tool steel developed by Mushet was looked upon largely as a curiosity. Gradually, however, the managers of machine shops found that by using tools made from the Mushet steel they were able to cut hard forgings and castings which were difficult to cut with the carbon tools. When this knowledge became quite

general, it was usual for the best machine shops to have a few Mushet tools on hand for use on specially difficult work, and their use for this purpose grew steadily from year to year.

955 It was not, however, until about 1890 that there was at all a general awakening among managers of machine shops as to the whole question of the cutting speeds of tools, and it may be said that practically up to that time Mushet tools had not been used for the purpose of gaining an increase in cutting speed. In fact, up to the time of our experiments of 1894–95, described in Part I, paragraphs 102, and Part 2, paragraph 956, but few machines, if any, had had their driving speeds increased with a view to using the possible gain in cutting speed obtainable through Mushet or other self-hardening tools.

EXPERIMENTS COMPARING MUSHET AND OTHER SELF-HARDENING AND CARBON TOOLS

956 It was in 1894 that we first had the opportunity to make a careful series of experiments to determine the relative cutting speeds of the Mushet and the carbon tools. We had hitherto been prevented from doing so by the fact that the Midvale Steel Works manufactured and sold tool steel, and up to the time the writer left their employ, they had not gone into the manufacture of self-hardening steel, and therefore would not allow us to make any experiments with it.

957 Our experiments in 1904–95 resulted in the following important discoveries:

958 *a* That, comparing the self-hardening steel with carbon steel, a gain in speed of 41 per cent to 47 per cent could be made in cutting a hard forging of about the quality of tire steel; whereas a gain of nearly 90 per cent could be made in cutting the softer qualities of metal; and

959 *b* that by using a heavy stream of water on the nose of a Mushet or other self-hardening tool, a gain of about 30 per cent could be made in the cutting speed.

960 These experiments, then, indicated clearly that the use of Mushet steel almost exclusively for cutting exceedingly hard pieces of metal was the wrong one; since an enormously greater percentage of soft metal was cut in the average machine shop than of hard metal, and the gain in cutting soft metals was 90 per cent as against only a 45 per cent gain for hard. It thus became evident that instead of using self-hardening tools only occasionally for cutting extra hard pieces of metal, they should be used daily throughout the shop on all ordinary work in place of the carbon steel tools. From that time on the increase in the use of self-hardening steels was so very

great that at the time of our invention of the new high speed tools, probably from one-fourth to one-fifth of the roughing tools used in good machine shops had come to be made from self-hardening steel.

961 Between 1885 and 1895 a few manufacturers of tool steel started to imitate the Mushet steel, and in the latter part of this period it was discovered that by substituting chromium for manganese in combination with tungsten a good self-hardening or "air-hardening" tool could be made. After 1890 the competition in the manufacture of self-hardening tool steels grew much more keen; but it is a remarkable fact that the successors to Mushet in the tool steel business, even up to the time of the Taylor-White invention, probably retained one-half of the business in self-hardening tool steel throughout the world. This is an unusual record for any one firm in the manufacture of any standard article.

962 As described in Part 1, paragraphs 102 to 110, at the time that we discovered the beneficial results from heating chromium-tungsten tools near to the melting point, tools made by several makers of tool steel, containing largely chromium and tungsten as the self-hardening elements in place of the manganese and tungsten used by Mushet, had equaled in cutting speed the Mushet self-hardening tools.

963 Up to 1894 may be called the era of carbon tools. From 1894 to 1900 when high speed cutting tools, treated by the Taylor-White process, were exhibited at the Paris Exhibition may be called the era of Mushet or self-hardening roughing tools. From 1900 up to the present time may be called the era of high speed tools, and this has become so completely the case that at the present time a carbon or an "untreated" tungsten-manganese or tungsten-chromium roughing tool can scarcely be found in an up-to-date machine shop.

NATURE OF THE INVENTION OF MODERN HIGH SPEED TOOLS

964 In paragraphs 102 and 110 the writer has described the circumstances leading up to the discovery of the facts embodied in the invention of modern high speed tools. There exists in the minds of most users of these tools a serious misapprehension both as to the nature of the invention and also as to that property in high speed tools which chiefly gives them their value. Perhaps at least four out of five writers upon the subject of high speed tools speak of the "discovery" or "introduction of high speed tool steels," as though our invention consisted in the discovery of a TOOL STEEL new in its chemical composition. The fact is, however, that tool steel of excel-

lent quality for making high speed tools existed and was in common use several years before our discovery was made.

THE QUALITY OF "RED HARDNESS"

965 A second misapprehension exists on the part of most people as to the nature of that property which enables the "high speed" tools to be run at their high speeds. Heating these tools (in a revolutionary manner) up close to their melting point is quite commonly referred to by writers on this subject as "hardening" the tools. In point of fact the high speed tools at their very hardest are little, if any, harder than the carbon tools, or the old fashioned self-hardening tools, and the quality of hardness is not that which enables them to run at very high speed.

966 Heating chromium-tungsten tools close to the melting point does not give them a degree of hardness which is unusual in tools, but it does give them the entirely new and extraordinary property of retaining what hardness they have, even after the tool has been heated up in use through the pressure and friction of the chip, until it is almost, or quite, red hot. This new property in high speed tools has been very appropriately named "RED HARDNESS," because the tool maintains its cutting edge sufficiently sharp and *hard* to cut steel even after its nose is *red hot*, and because in many cases it heats up the chip or shaving which it is cutting until the portions of the chip which are exposed to the friction of the tool become red hot.

967 The fact that hardness of the kind to which we have been accustomed in ordinary tools has but little to do with high speed tools is graphically illustrated on Folder 3, Fig. 18. This is one of the high speed tools of the most approved chemical composition referred to in Folder 21, tool No. 27, and this very tool was run at as high a cutting speed as the high speed cutting tools originally developed by us. After running at its high speed, the two deep indentations or nicks were filed with a file made from ordinary carbon tool steel, one across the cutting edge and the other about $\frac{1}{2}$ inch below the cutting edge, showing that a first-class high speed tool can be readily filed by the old carbon tool steel.

968 As to our invention, briefly speaking, by far the most important of the several discoveries made by us, and which led to the modern high speed tools, was the discovery that when tools made from tool, steel old in its chemical composition (containing not less than one-half of one per cent of chromium and not less than one per cent of tungsten, or its equivalent) were treated in a new and completely

revolutionary manner to an extraordinarily high heat (a heat so high that it would have utterly ruined ordinary tools), this treatment imparted an entirely new quality or property to a cutting tool, namely the property called "red hardness"; and it is this new property which enables these tools to run at their high cutting speeds.

GENERAL COMPARISON OF THE INGREDIENTS OF CARBON TOOLS, SELF-HARDENING TOOLS AND MODERN HIGH SPEED TOOLS

969 Chemically speaking, the era of carbon tool steel may be said to consist of tools containing from ¾ per cent to 1½ per cent of carbon in combination with a little manganese and silicon (used to help in melting, casting, and hammering the steel), the rest of the steel being iron.

970 The era of self-hardening tools may be said to consist of about 4 to 11 per cent of tungsten in combination with 1½ per cent to 3½ per cent of manganese with 1¼ to 2¼ per cent of carbon; and to these ingredients chromium to the extent of from three-tenths of one per cent to almost 3 per cent was used either as a substitute for the manganese or in addition to it. The rest of the steel consisted of iron with a small amount of silicon used for melting purposes.

971 The era of high speed tool steel may be said to consist of tools containing one-half of one per cent or more of chromium in combination with one per cent or more of tungsten, or its equivalent of molybdenum heated almost to the melting point. The percentages of chromium and tungsten used in high speed tools vary between extremely wide limits. The "one-half per cent or more" of chromium referred to in our patent has been increased in the extreme case to the extent of 7 per cent, and the "one per cent or more" of tungsten has been increased in the extreme case to 26 per cent. The percentage of carbon, on the other hand, has been lowered until the better modern tool steels contain from fifty-five one-hundredths of one per cent to about 1¼ per cent as the maximum, and the manganese, silicon and other ingredients have been reduced to quantities sufficient merely for good melting. As above explained, molybdenum has been substituted for the tungsten as an equivalent or mixed with the tungsten. Our experiments, however, would indicate that this element is not as desirable as tungsten.

ADDITION OF VANADIUM IN SMALL QUANTITIES IMPROVES QUALITY OF HIGH SPEED TOOLS

972 During the year 1906 our experiments indicate that the addition of a small amount of vanadium, from twenty-five one-hundredths of one per cent to one-half of one per cent, chemically improves the quality of high speed tools, and the best chemical composition which we know of for high speed tools is the following, recently developed by us:

TUNGSTEN	CHROMIUM	CARBON	MANGANESE	VANADIUM	SILICON	PHOSPHORUS	SULPHUR
18.91	5.47	0.67	0.11	0.29	0.043		

GENERAL ON THE TREATMENT OF HIGH SPEED TOOLS NO IMPROVEMENT HAS BEEN MADE IN THE HEAT TREATMENT OF HIGH SPEED TOOLS SINCE THE DISCOVERY BY MESSRS. WHITE AND TAYLOR IN 1889-1899

973 Seven years have now gone by since Mr. White and the writer applied for our patents covering the Taylor-White process of making and treating tools, and it is an extraordinary fact that so far as the writer knows, not a single improvement has been made upon the method of heat treatment for producing the high speed lathe and planer and other metal cutting tools described in this patent.

974 During the summer and fall of the present year (1906), we have procured those makes of tool steel which have recently attained the highest reputation for efficiency in England, Germany and America, and have conducted a careful series of experiments with tools shaped and ground exactly alike, in cutting both steel and cast iron of uniform qualities, in order to determine both what chemical composition and what heat treatment would produce a tool of the highest cutting speed.

975 In all cases we obtained detailed instructions from the makers of the steels, telling us just what heat treatment to give tools made from their steels and in some cases men were sent by the manufacturers to superintend the heat treatment of their tools. In all instances we treated each brand of tool steel exactly as directed and then tested the tools to determine their fastest standard cutting speeds.

976 In addition to this, similar tools in most cases the same, made from each make of tool steel were treated in exact accordance with the method indicated in our patent No. 668269 of February 19, 1901, as our preferred method. And without an exception, the same make of tools, when treated in exact accordance with the directions given in our patent, proved more uniform and ran at slightly higher cutting speeds than when treated in accordance with the directions given by the makers.

977 This result is extraordinary, indeed we believe almost unique, in the history of an invention so fundamental and revolutionary in its character. Moreover, the writer must confess to the greatest surprise that although subject to innumerable experiments throughout the entire manufacturing world, the method of treating these tools should not have been radically improved during all these years.

978 For detailed directions as to that heat treatment which will give the very best results in the new high speed tools, therefore, the writer refers all readers to the directions given in the patent above referred to. However, since in past years there has been difficulty at times in obtaining copies of this patent from the Patent Office, we will briefly recapitulate the most important directions for treating modern high speed tools.

FIRST OR HIGH HEAT TREATMENT FOR HIGH SPEED TOOLS. HEATING TOOLS CLOSE TO THE MELTING POINT

979 After the lathe or planer tool has been forged, as described in paragraphs 431 to 471, the entire nose of the tool should be slowly and uniformly preheated to a bright cherry red, allowing plenty of time so that the heat may penetrate thoroughly to the center of the tool and thus avoid danger of cracking from too rapid heating. From the bright cherry red up to the melting point, on the other hand, the tool should be heated as rapidly as practicable in an intensely hot fire until the nose begins to soften. In fact, if the extreme exposed portions of the nose are slightly fused no harm will be done. In this operation also thorough and uniform heating is necessary, and time should be given for the whole nose of the tool to arrive at a uniform temperature.

980 No method or apparatus should be used for giving the tools the high heat treatment which heats only a portion of the nose of the tool. The whole end of the tool from the heel to the lip surface should be uniformly heated to the same high heat.

981 If the fire gives a sufficiently intense heat, a tool of 2 inch by 3 inch body can be thoroughly and properly heated in three minutes

from a bright cherry red up to the proper high heat. Without an especially designed furnace, however, it is difficult to obtain a sufficiently uniform and intense heat to treat a tool of this size in three minutes. Smaller tools require from three-fourths of a minute upward, according to the intensity of the fire and the size of the tool, to heat from the cherry red to the high heat.

982 The writer wishes to again emphasize the importance of an intensely hot fire. Various methods for producing this high heat will be referred to in paragraphs 1007 to 1010. If the nose of the tool is exposed to the high heat for too long a time, or if a fire is used which does not give an intensely hot flame, the extreme outside layers of the tool are sometimes slightly injured, probably through oxidization. Therefore, in designing cutting tools, where practicable, they should be forged so as to allow from $\frac{1}{16}$ to $\frac{1}{8}$ of an inch to be ground off at the first grinding. This will insure immediately a tool having the highest cutting speed. It is for this reason that in Folder 5, Figs. 25d to 25e we indicate in dotted lines above and beyond the upper part of the nose of the tool the shape to which the tool should be forged, and in heavy lines the shape to which the tool should be ground at its first grinding.

COOLING HIGH SPEED TOOLS FROM THE HIGH HEAT

983 In paragraphs 1006 to 1009 we have referred to a certain range of temperatures between 1550 degrees Fahr. to 1700 degrees Fahr., called the breaking down temperatures, and have called attention to the fact that the old fashioned self-hardening tools if heated to within this range of temperatures were seriously injured or broken down in their cutting speeds.

985 To get the best and most uniform results with high speed tools after their high heat has been given them, as above described, they should be cooled rapidly until they are below the breaking down point, or, say, down to or below 1550 degrees Fahr. The quality of the tool will be but little affected whether it is cooled rapidly or slowly from this point down to the temperature of the air. After all parts of a tool from the outside to the center have reached a uniform temperature below the breaking down point, therefore, it is our practice sometimes to lay it down in any part of the room or shop which is free from moisture, and let it cool in the air, and sometimes to cool it in an air blast to the temperature of the air.

986 We have found the best method of cooling from the high heat to below the breaking down point to be that of plunging them into a

bath of red hot molten lead below a temperature of 1550 degrees Fahr. We now plunge them into a lead bath maintained at a uniform temperature of 1150 degrees Fahr., because the same bath is afterward used for reheating the tools to give them their second treatment. This bath should contain a sufficiently large body of the lead so that its temperature can readily be maintained uniform; and for this purpose we use preferably a lead bath containing about 3600 pounds of lead.

987 The largest sized tool when plunged at the high heat into a bath of this size will not materially affect the temperature of the lead. If too small a lead bath is used and one tool after another is plunged into it from the high heat, before, say, the first tool plunged has been cooled uniformly to the temperature of the bath, the lead may possibly be heated to a higher temperature than it had originally, and this rise in the temperature of the lead, if it were to extend beyond 1240 degrees while the tool is in it, would seriously injure the tool.

988 Too much stress cannot be laid upon the importance of never allowing a tool to have its temperature even slightly raised for a very short time during the process of cooling down. The temperature must either remain absolutely stationary or continue to fall after the operation of cooling has once started or the tool will be injured. Any temporary rise of temperature during cooling, however small, will injure the tool. This, however, applies only to cooling the tool to the temperature of about 1240 degrees, Fahr. Between the limits of 1240 degrees and the temperature of the air the tool can be raised or lowered in temperature time after time and for any length of time without injury. And it should also be noted that during the first operation of heating the tool from its cold state to the melting point no injury results from allowing it to cool slightly and then be reheated. It is from reheating during the operation of cooling from the high heat to 1240 degrees Fahr. that the tool is injured.

989 The above described operation is commonly known as the first or high heat treatment.

990 To briefly recapitulate, the first or high heat treatment consists of heating the tool:

a slowly to 1500 degrees Fahr.;

b rapidly from that temperature to just below the melting point;

c cooling fast to below the breaking down point, *i. e.*, 1550 degrees;

d cooling either fast or slow from this point to the temperature of the air.

THE SECOND OR LOW HEAT TREATMENT

991 This treatment consists in reheating the tool which has had the high heat treatment to a temperature somewhere between 700 and 1240 degrees Fahr., rather better results being obtained at the higher temperatures within these limits.

992 For this reheating the best practice is to place the tool in a lead bath containing about 3600 pounds of lead, the temperature of which can be maintained uniform within a few degrees of 1150 degrees Fahr. by means of our exceedingly simple optical pyrometer, and then either cooled in an air blast or laid down to cool in the air. The tool should be held in this bath about 5 minutes. To avoid danger of fire cracks, particularly if the tool is of complicated shape, it should be heated rather slowly before being plunged into the lead.

993 We have fixed upon 1150 degrees as the temperature of the lead bath because, even with a sluggish bath slow in either increasing or lowering its temperature, there is danger through carelessness on the part of the operator of allowing its temperature to rise, and so heating the tool beyond the critical temperature of 1240 degrees. If the tool is allowed even for a short space of time to rise in temperature beyond 1240 degrees its property of red hardness will be seriously impaired, and its cutting speed greatly reduced; and a rise in temperature beyond 1350 degrees will completely destroy the property of red hardness in the tool and leave it in its original condition before receiving the high heat treatment.

994 To briefly recapitulate, the second or low heat treatment consists of heating the tool:

a to a temperature below 1240 degrees, preferably to 1150 degrees for a period of about 5 minutes; and

b cooling to the temperature of the air either rapidly or slowly.

995 The good effects of the second or low heat treatment can be produced in another way, by running the tool under the friction of the chip until the temperature of its nose has been raised to within the limits of, say, 700 degrees, to 1240 degrees Fahr. Having been heated under the pressure of the chip in this manner, and then cooled to the temperature of the air, the next time that it is run the tool will have a materially increased degree of red hardness and can be run at a higher cutting speed than it was capable of maintaining after the high heat and before the low heat treatment.

UNIFORMITY THE MOST IMPORTANT QUALITY IN CUTTING TOOLS

993 The writer has many times referred to the necessity of uniformity in the various standards adopted, and we therefore consider uniformity in the red hardness of tools and in their cutting speeds to be the most important element or property sought for.

997 Within one month after having discovered the Taylor-White process we had succeeded in developing a number of tools which were capable of running at as high speeds in cutting steel of medium and soft quality and of lasting as well as any tools developed by us up to the date of application for our patent. The greater part of the time given by us to the development of high speed tools was spent in the effort to obtain uniformity in the tools. The writer looks upon uniformity as of such importance that he does not hesitate to assert that with proper task management more work can be gotten out of a shop with the old fashioned uniform Mushet tools than from a shop without task management and with new high speed tools which are as far from being uniform as they now are in many shops.

998 Under task management it is of great importance that the workman be fully convinced that the man who operates the slide rule and gives him his speed directions is able to tell him with regularity how to remove metal faster than he could remove it without these directions. Without uniform tools, however, the slide rule man will find himself almost as much at sea as the workman, and thus will be completely discredited in the eyes of the latter.

999 It is then for the purpose of obtaining uniformity in the tools that our method and apparatus described above for the high and low heat treatments are particularly desirable. It is a very curious fact connected with the development of high speed tools that there are a great number of ways of giving the high and low heat treatments which will produce first class tools. Perhaps three out of four tools given the high and low heat treatments in these various ways might be called first-class tools. Our method as described above, however, will produce tools which are practically all first-class, and it is for this reason that we recommend its adoption in all shops in which a sufficient number of tools are treated each day or each week to warrant the expense of maintaining lead baths controlled by accurate pyrometers and a proper furnace for giving the high heat.

1000 It would be manifestly improper for the writer to describe in minute detail the apparatus developed by us for this purpose, because some features of the apparatus were patented, while others were mere questions of proportions and design, and the whole of the patents,

apparatus and methods, were sold by us to the Bethlehem Steel Company after making the invention. (See paragraphs 990 and 994)

LITTLE ATTENTION NEED BE PAID TO THE SPECIAL DIRECTIONS GIVEN BY MAKERS OF HIGH SPEED TOOLS FOR THEIR TREATMENT. ALL GOOD HIGH SPEED TOOL STEELS SHOULD BE TREATED IN THE SAME SIMPLE WAY

1001 For some years past it has been rather amusing to us to hear the special directions given by the various manufacturers of steel suitable in chemical composition for making the high speed tools. Very frequently a tool steel maker implies, or directly states that the chemical composition of his particular high speed tool steel requires "special treatment." The fact is, however, as stated above, that our recent experiments demonstrate beyond question the fact, that no other method which has come to our attention produces a tool superior in red hardness (*i. e.*, high speed cutting ability), or equal in uniformity to the method described inparagraphs 979 to 994. This applies to all makes of high speed tool steels which are capable of making first-class tools, whatever their chemical composition.

1002 It is the writer's belief that during our long series of experiments at the Bethlehem Steel Company, in our search for uniform tools and for the method of imparting the highest degree of red hardness to tools, we tried substantially every method which since that time has come to our attention.

1003 For instance, in giving the tools the high heat we heated them in a blacksmith's coke fire, a blacksmith's soft coal fire, in muffles over a blacksmith's fire, and in gas heated muffles. We also constructed various furnaces for this purpose. We heated the tools by means of an electric current, with their noses under water, and out of water, and by immersion in molten cast iron. Moreover, by every one of these methods we were able to produce a first-class tool provided only the tool was heated close to the melting point.

1004 In cooling from the high heat we experimented with a large variety of methods. After being heated close to the melting point, tools were immediately buried in lime, in powdered charcoal, and in a mixture of lime and powdered charcoal; thus they were cooled extremely slowly, hours being required for them to get below a red heat. And we wish to clearly state the fact that tools cooled even as slowly as this, while they were in many cases quite soft and could be filed readily, nevertheless maintained the property of "red hardness" in as high a degree as the very best tools, and were capable of cutting the medium and softer steels at as high cutting speeds as the best

tools which were cooled more rapidly; and which were much harder in the ordinary sense.

1005 Tools were also cooled from the high heat in a muffle or slow cooling furnace with a similar result. On the other hand, we made excellent high speed tools by plunging them directly in cold water from the high heat, and allowing them to become as cold as the water before removing them. Between these two extremes of slow and fast cooling; cooling in lime, charcoal, or a muffle, on the one hand, and in cold water, on the other; other cooling experiments covering a wide range were conducted. We tried cooling them partly in water and then slowly for the rest of the time; partly in oil, and then slowly for the rest of the time; partly by a heavy blast of air from an ordinary blower and the rest of the time slowly; partly under a blast of compressed air and then slowly. We also reversed these operations by cooling first slowly and then fast, as described. We also cooled them entirely in an air blast and entirely in oil, and then partly first in oil, afterward in water, and then first in water and afterward in oil.

1006 By every one of these methods we were able to make a good high speed tool; *i. e.*, a tool having a large degree of red hardness, and capable of cutting at very high cutting speeds. But by none of these processes were we able to obtain tools as uniform and regular as those produced by our lead bath and air cooling.

BEST METHOD OF TREATING TOOLS IN SMALL SHOPS

1007 There are many very small shops in which it is questionable whether the installation of the full apparatus required to treat tools by our preferred method would be warranted. For this class of shops, in treating high speed tools, the writer considers the best method to be as follows, for the blacksmith who is equipped only with the apparatus ordinarily found in a smith-shop:

1008 After the tools have been forged and before starting to give them their high heat, fuel should be added to the smith's fire so as to give a good deep bed either of coke about the size of an English walnut or of first-class blacksmith's soft coal. A number of tools should then be laid with their noses at a slight distance from the hotter portion of the fire so that they may all be pre-heating while the fire is being blown up to its proper intensity. After reaching its proper intensity, the tools should be heated one at a time over the hottest part of the fire as rapidly as practicable up to just below their melting point. During this operation they should be repeatedly turned over and over so as to insure a uniform high heat throughout the whole end of the tool. As soon as each tool reaches its high heat, it

should be placed with its nose under a heavy air blast and allowed to cool to the temperature of the air before being removed from the blast.

1009 Unfortunately, however, the blacksmith's fire is so shallow that it is incapable of maintaining its most intense heat for more than a comparatively few minutes, and, therefore, it is only through these few minutes that first-class high speed tools can be properly heated in the smith's fire. Great numbers of high speed tools are daily turned out from smiths' fires which are not sufficiently intense in their heat, and they are therefore inferior in red hardness and produce irregular cutting tools.

COKE FIRE PREFERABLE TO SOFT COAL FOR HEATING TOOLS CLOSE TO MELTING POINT IN AVERAGE SMITH SHOP

1010 On the whole, a blacksmith's fire made from coke may be regarded as better for giving the high heat to tools than a soft coal fire, merely because a coke fire can be more easily made by the smith which will remain capable for a longer period of heating the tools quickly to their melting points. We have, however, recently made some very careful experiments in which, out of a lot of tools made from practically the same steel, each alternate tool was heated in the best type of coke fire and the best type of soft coal fire, and in every case a notably better tool was produced by the first-class soft coal fire. An improvement of fully 4 to 8 per cent was made by the soft coal over the coke tools. This is undoubtedly due to the fact that a first-class soft coal fire liberates large amounts of hydro-carbons which give an intense heat and are less likely to oxidize the steel than a correspondingly hot flame produced from coke.

1011 Nevertheless, for the reasons given above, our advice is to use a coke fire and make it as deep as practicable. This is for the sake of securing uniformity. We have found it practically impossible to prevent smiths from giving tools their high heat in the soft coal fire long after the fire has passed that period of intensity which is suited to the high heat treatment. When the air blows through the fire and strikes the hot tool, it appreciably injures the outer layers of the steel to the depth of from $\frac{1}{16}$ inch to $\frac{3}{16}$ inch.

1012 Cooling a tool in an air blast from high heat will produce as good and uniform a tool as can be made by any other method outside of that of plunging it into the hot lead bath, as described in paragraphs 985 to 988.

1013 All of the more rapid methods of cooling the tool, either through plunging it into water or oil, render the tool more liable to

fire cracks, and also more brittle in its body and liable to break in service, particularly when there is any lack of uniformity in the heating, and at the same time cooling in water or oil gives no greater degree of "red hardness" than can be obtained through blowing in the air. And this applies without exception to all steel of the chemical composition suited to making the better modern high speed tools. No attention whatever need be paid to any other special directions given by the makers.

1014 The one question about high speed tools which more than any other has been asked the writer for years past is: "Where can absolutely uniform high speed tool steel be bought?" and the writer's invariable answer has been: "Any one of the first-class makes of high speed tool steel is amply good. The trouble does not lie with the lack of uniformity of the tool steel. The main trouble is that you have not yet stolen the whole of the invention. You had better go back and steal it all."

1015 Several types of apparatus have been developed for giving high speed tools their first or high heat treatment as well as for giving them their second or low heat treatment. For a description of some of these the writer would refer to Mr. Gledhill's admirable paper above mentioned, on "The Development and Use of High Speed Tool Steel," and also to an article by Messrs. O. M. Becker and Walter Brown in the "Engineering Magazine" for November, 1905.

IMPORTANCE OF NOT OVERHEATING HIGH SPEED TOOLS IN GRINDING

1016 The writer trusts that he has made the fact clear that the property of red hardness in tools is seriously impaired by even temporarily raising their temperature beyond 1240 degrees Fahr. He ventures to say that fully half of the high speed tools now in use in the average machine shop have been more or less injured, and are therefore lacking in uniformity, owing to their having been overheated during the operation of grinding. Even when a heavy stream of water is thrown upon the nose of the tool throughout the operation of grinding, tools can be readily overheated by forcing the grinding or by allowing the tool to fit against the grindstone, as explained in paragraph 481. This injury is all the more serious because there is no way of detecting it except by finding through actual use that the tool has become of inferior quality. The writer has frequently seen tools which were ground under a heavy stream of water heated so that the metal close to their cutting edges showed a visible red heat.

1017 Occasionally tools are also overheated by running at too high speeds in the lathe. In this case, however, the injury to the

tool is perfectly apparent, and therefore not so serious as the overheating on the emery wheel.

1018 A tool which has been overheated either in grinding or in the machine can be again rendered first-class in quality by grinding it from $\frac{1}{16}$ inch to $\frac{3}{16}$ inch back from the cutting edge and down from the lip surface, because overheating from grinding or running in the lathe rarely penetrates beyond this depth.

1019 The best advice that we can give to those desirous of having uniform tools is not to experiment with new brands of tool steel. Adopt once for all the best that can be had at the time the choice is made, and then see to it that the smith heats each tool uniformly and rapidly close to the melting point, and that the grinder does not overheat the tool in sharpening it. Watch the smith and the grinder, do not change the make of the tool steel.

THE CHEMICAL COMPOSITION OF TOOL STEEL

FOLDER NO. 20 GIVING THE ANALYSES AND CUTTING SPEEDS OF MANY OF THE LATEST HIGH SPEED TOOLS, AND A COMPARISON OF THESE TOOLS WITH MUSHET SELF-HARDENING TOOLS AND THE ORIGINAL HIGH SPEED TOOLS AS DEVELOPED BY MESSRS. TAYLOR AND WHITE

1020 The best tool steel should be capable of producing high speed tools of the following qualities or characteristics:

LIST OF THE MORE IMPORTANT CHARACTERISTICS OF HIGH SPEED TOOLS

1021 (A) Tools should be of such composition that comparatively small errors or imperfections in the heat treatment will not seriously injure them and thus render them irregular in their cutting speeds. That is, the steel should be of that composition from which it is easy to make uniform tools.

1022 (B) Tools should not fire crack easily from the heat treatment.

1023 (C) Tools should be capable of running at the highest standard speed in cutting either hard, medium, or soft steel; or hard, medium or soft cast iron.

1024 (D) Tools should be difficult to ruin on the grindstone or through overheating in the lathe.

1025 (E) Tools should be tough in the body; *i. e.*, not liable to break in use even when receiving severe jars or blows from the work.

1026 (F) Tools should be capable of taking fine feeds in cutting hard metals with proportionally high cutting speeds as when taking coarse feeds.

1027 (G) Tools should be easy to dress or shape without requiring very high heat.

1028 (H) When injured through use in the lathe, the quality of the tool steel should be such that the injury can be repaired by grinding off as small amount as practicable from the tool.

1029 No tool steel has yet been developed which possesses all these qualities in the highest degree. It is, however, a most interesting and useful fact that the tool steel marked No. 1 in Folder 20, Table 128, possesses all except two of these qualities in as high a degree as any steel that we have tested. The two defects possessed by this steel are that it is rather difficult to forge into a tool; and although it is very tough in its body, it is not as tough as tools whose bodies are either annealed or partially annealed.

CHEMICAL ANALYSES AND CUTTING SPEEDS OF THE BEST MODERN HIGH SPEED TOOLS

1030 In Folder 20, Table 128, we give the chemical composition of various makes of tool steel now in use, and we believe that this list contains the most noted, and as far as we know the best English, German and American brands of high speed tool steels. Opposite each make of tool will be found its standard speed, 20 minutes duration, $\frac{3}{16}$ inch depth of cut, $\frac{1}{16}$ inch feed, in cutting:

a Medium tool steel about 0.34 per cent carbon, 73,000 lbs. tensile strength, 30 per cent stretch;

b very hard annealed tool steel, about 1 per cent carbon, 100,000 lbs. tensile strength, 6 per cent stretch; and

c very hard cast iron.

1031 It has been our experience that a tool capable of cutting metal of these three qualities at high speeds is also capable of cutting at correspondingly high speeds almost any other quality of steel or cast iron which is softer than those given. Tools are sometimes found which will cut the very hard metals at high speeds, and yet not do proportionally well on the medium metals; but if they cut both the very hard and the medium, our experience is that they are equally good for anything softer. Many tools can be found, however, which cut softer metals well and yet fall down badly in cutting hard steel or hard cast iron.

1032 We are just completing (October 20, 1906) a series of tests with the tools upon the forgings and castings just referred to. In addition to this we have tested in cutting the same pieces of metal the old fashioned carbon tools of the Jessop make; two Mushet tools, one used by us in our former experiments, and the other an especially fine quality of Mushet tool dating back to the early 90's; also tools used by us in our experiments for developing the Taylor-White process, which resulted in high speed tools. In addition to these, we have also tested upon the same forgings and castings some of the tools used by us since the Bethlehem experiments in determining the laws for cutting metals referred to in paragraphs 770 to 814; and some of the tools used by us in experiments made since the Bethlehem experiments to determine the chemical composition of those high speed-tools which at that time ranked first.

RECENT COMPARISON OF CUTTING SPEED OF BEST MODERN HIGH SPEED TOOLS WITH THAT OF FORMER TYPICAL TOOLS

1033 Our objects, then, in making the series of experiments whose results are tabulated on Folder 20, Table 138, are first, that having determined the best steel to use for making modern high speed tools, we might clearly connect this information with practically all of our past experiments. (This is important principally for the purpose of modifying all of the laws and formulæ obtained by us, so as to bring them completely up to date and make them accord with the tools made from the best tool steel now known), and second, because as an interesting historical fact, they indicate as accurately as practicable the progress made in proceeding step by step from the carbon tools to the best modern high speed tools.

THE BEST CHEMICAL COMPOSITION FOR MODERN HIGH SPEED TOOLS

1034 By referring to Folder 20, Table 138, it will be noted that while No. 1 tool is in all respects better than any of the others, yet the differences in cutting speeds are comparatively small between this tool and several of those following it. Therefore the users of tool steel cannot go far wrong by adopting any one of these noted brands of tool steel, but having once adopted a make of tool steel we would strongly advise against changing, and particularly against allowing any other steel to be used in the same shop.

CARBON TOOL STEELS

TABLE GIVING THE ANALYSES OF SELF-HARDENING AND ORDINARY CARBON TOOL AS USED BEFORE THE DISCOVERY OF HIGH SPEED TOOLS

1035 Folder 22, Table 140, affords an interesting study of the relations between the chemical composition of various tool steels and their cutting speeds. Beginning with the analyses of carbon tool steels, by referring to Folder 22, Table 140, Nos. 85 to 89, it is apparent that but small differences exist in the cutting speeds of the various makes; in fact, when cutting the same quality of metal, the cutting speeds do not vary more than 6 per cent.

TOOLS WHICH ARE NOT SELF-HARDENING AND YET CONTAIN TUNGSTEN OR CHROMIUM

1036 Analyses Nos. 82 to 84 include several tools which must be hardened and tempered in the old fashioned way to be of any use; and yet to these steels have been added the two metals which when combined in sufficient quantities produce self-hardening tools. A study of the chemical compositions of these steels is chiefly interesting for two reasons:

1037 First, because they illustrate the fact that the presence of tungsten even to the extent of 7 per cent as in the case of No. 83 (the Eicken) produces a tool which has no more self-hardening properties than ordinary carbon steel, the reason for this being that there is but an exceedingly small amount of either manganese or chromium present; and also that, as in the case of No. 84 (Midvale chrome-crucible), a tool may contain 1.6 per cent of chromium (an ample percentage to make good self-hardening steel if either tungsten or molybdenum were present) and still have no self-hardening properties.

1038 Second, because they show clearly that the addition of 1.6 per cent of chromium coupled with 0.71 per cent of carbon (a very low carbon for a tempered tool steel) and also with 0.10 per cent manganese (a decidedly low manganese for a tempered tool steel) gives the tool a materially higher cutting speed than that of the ordinary carbon tempered tools.

1039 We made a very exhaustive examination of this steel, but the fact that it required more skill on the part of the blacksmith in judging its proper hardening heat than the ordinary carbon tools prevented its adoption as a standard shop tool, even although tools of this composition could be run at a cutting speed materially higher than the

carbon tempered tools. The cutting speed of these tools was about halfway between that of the carbon and the self-hardening tools; but if heated a little too high they were apt to fire crack in hardening, and our experience with fire cracks in tools leads to the conclusion that great damage is likely to be done through their breaking in daily use. Therefore when a steel, either carbon, self-hardening, or of the modern high speed tool variety, shows any marked tendency to fire crack or toward brittleness, we promptly abandon all idea of its adoption as standard. The writer calls attention to this fact chiefly because later, in considering the more important question of the proper chemical composition for high speed tools, it will be observed that many tools whose cutting speeds and other qualities entitled them to consideration were promptly abandoned because they showed a marked tendency toward fire cracking or brittleness.

1040 However, the steel represented in Analysis 83 excels in one respect all carbon steels which have come to our attention. It is admirably suited to finishing extremely hard metals, and, in spite of its requiring a low hardening heat, is an excellent standard for this special purpose.

1041 On Folder 22, Table 140, Nos. 65 to 81, we give the analyses of several self-hardening tools made between the dates of 1893 and 1898; and of these, Nos. 65, 66, 67, 68, and 33, were experimented with by us at the Bethlehem Steel Company just prior to the discovery of the Taylor-White process while searching for the best self-hardening steel to adopt as a shop standard for that company. Many other brands of self-hardening tools had been tested previously by us as to their cutting speeds but because of evident inferiority to the above brands were not analyzed or tested at this time. These five makes of tool steel, then, are interesting because they represent, so far as we know the best self-hardening steels then in the market, and the only makes which we believed to be worthy the expenditure of time and money required in making careful standard speed tests on the experimental lathe. It is notable that two steels out of the five (Mushet and Firth-Stirling) depended for their self-hardening properties upon a comparatively large percentage of manganese in combination with tungsten, while three of them depended mainly upon high chromium in combination with tungsten or molybdenum. It will be observed that No. 68 (Midvale) gave the highest cutting speed, but, as explained in Part 1, paragraphs 106 to 109, this steel was seriously injured in the operation of heating by the blacksmith, which injury led to the discovery of the Taylor-White process. It is highly likely, therefore, that had not the high speed tools been discovered,

the Mushet self-hardening steel No. 68 would have been adopted by us as our standard in spite of the slightly higher cutting speed of the Midvale steel, since, as explained, the Mushet steel gave evidence of overheating by the blacksmith through crumbling when hammered. Thus the Mushet tools, when injured by overheating, remained in the blacksmith shop, while overheated Midvale tools were likely to get into the machine shop and interfere seriously with the uniformity in the shop tools.

TABLE GIVING ANALYSES AND CUTTING SPEEDS OF VARIOUS TOOLS EXPERIMENTED WITH BY MESSRS. TAYLOR AND WHITE IN THE DISCOVERY AND DEVELOPMENT OF THE NEW HIGH SPEED TOOLS

1042 On Folder 21, Table 139, are given the chemical compositions of various steels experimented with by us during the time of the discovery and development of the new high speed tools by Mr. White and the writer. These tools are separated into various groups for the purpose of showing the relative effect of comparatively large and small quantities of each of the following elements upon the cutting speed; namely, tungsten, molybdenum, chromium, carbon, and manganese.

1043 After the columns giving the percentages of the various ingredients of which the tools are composed, two columns are found, in the first of which is entered the cutting speed of the steel when given the ordinary heat treatment as practiced before our invention, and as in many cases recommended and even superintended by the makers of the tool steel. In the second column are entered the speeds obtained by the same tools after having been treated carefully by the Taylor-White process of heating the tool close to the melting point, cooling it and then reheating it to about 1150 degrees Fahr.

1044 A study of the various groups of tools together with their cutting speeds before and after receiving the high heat treatment will make clear the basis of our claim in Patent No. 668269, that tools containing one half of one per cent or more of chromium and one per cent or more of tungsten, or its equivalent in molybdenum, are materially improved in cutting speed through the treatment by the Taylor-White process. This, however, is of minor interest. A subject of greater interest is the effect of the various elements when used in such quantities in the tool steel as to produce tools of the highest cutting speeds; that is, the highest degree of red hardness, when treated by the Taylor-White process.

DISCUSSION OF THE EFFECT OF EACH OF THE FOLLOWING ELEMENTS UPON HIGH SPEED TOOLS AS ORIGINALLY DEVELOPED— TUNGSTEN, CHROMIUM, CARBON, MOLYBDENUM, MANGANESE, SILICON

1045 By examining the chemical compositions of the tools given after Nos. 26 to 35 (namely, the groups of tools which after receiving the Taylor-White treatment gave the highest cutting speeds during the period of our invention), it will be noted, first, that no tool in this group contains less than 6½ per cent of tungsten and that the highest tungsten in this group is 8.75 per cent; second, that no tool in this group contains less than 1.62 per cent of chromium, and that the highest chromium is 3.94 per cent. It would seem, therefore (as a result of these investigations), that to produce what we considered at that time first class tools, the chromium and tungsten must be within these limits.

1046 The effect of low tungsten will be seen by examining tools Nos. 41 to 44. In No. 42 it will be noted that with 1.91 per cent of tungsten and 3.25 per cent of chromium, a tool was produced which improved materially upon being heated to a high heat, whereas tool No. 41 containing 0.83 per cent of tungsten and 3.80 per cent of chromium deteriorated materially in its cutting speed upon receiving the high heat treatment. From this it is evident that even with high chromium more than 0.83 per cent of tungsten is required in the tool before the property of red hardness begins to be apparent, and also that high chromium tools are injured in their cutting speeds when overheated, although of course not to the same extent as ordinary carbon tools.

1047 On the other hand, upon examining the carbon column we note that the lowest carbon which produced a first-class tool was 0.858 per cent while the highest carbon was 1.950 per cent. Between these limits, then, our experiments indicated that, as far as the effect of cutting speed was concerned, it was a matter of indifference whether low or high carbon was used. And it is a notable fact that many of the best high speed tools developed up to the present date contain carbon, in almost the same percentage as that indicated by the low limit in our experiments.

1048 At the time that we were developing our invention it was not usual to make self-hardening steel containing carbon in as small quantities as 0.86 per cent. An increase of carbon produces an increase in the hardness of a self-hardening tool, although, as indicated by the group of tools from No. 26 to No. 32, increasing carbon beyond 0.86

per cent does not produce a higher cutting speed or a greater degree of red hardness which is the distinctive quality of high speed tools. We had the 0.86 per cent carbon steel made especially for the purpose of testing the effect of low carbon upon red hardness in Taylor-White treated tools. And it was the statement made in our patent, that high heat treated tools containing 0.86 per cent of carbon gave as high cutting speeds as those containing high percentages of carbon, which first turned the attention of makers of tool steel in this direction.

1049 Our adoption of the higher limits of carbon at the time of the writing of the Taylor-White patent was upon the supposition that through heating the tool many times in succession to the high heat, the carbon lying in the outer layers of the nose of the tool might be considerably reduced, and that with high carbon this reduction of carbon would leave the tool as efficient as ever, whereas with carbon as low as 0.86 per cent any material reduction in carbon might affect its cutting speed.

1050 However, more recent experiments have shown that even with comparatively low carbon there is little danger of injuring the tool so that it cannot be repeatedly heated to the high heat from oxidization or burning out of the carbon in the outer layers of the tool; and in the best of the present high speed tools the rather low carbon of 0.68 per cent is used for the purpose of rendering the steel more readily forged to the proper shape, and also to make it rather less brittle in the body of the tool.

1051 Referring to the manganese column, it is notable that the lowest manganese is 0.07 per cent and the highest 1.19 per cent. It is clear then that low manganese does not affect the property of red hardness in high speed tools. Low manganese renders the tool stronger in its body, less liable to brittleness, less liable to fire crack, and more easily forged and annealed; and for this reason we recommended a steel low in manganese as best for the Taylor-White treated tools.

1052 By examining Folder 21, Table 129, the three groups of analyses, namely, the effect of high chromium and the effect of low chromium and the effect of low manganese, it will be noted that making a tool of high chromium with the proper amount of tungsten invariably produces a high speed tool even although the manganese is low; but that a tool without chromium or with very low chromium, even though there is a proper percentage of tungsten present, does not produce a high speed tool even though the manganese may be low or very high. From this it follows that chromium is the element which in combination with tungsten produces the new quality of red hardness and not manganese.

MOLYBDENUM AS A SUBSTITUTE FOR TUNGSTEN IN HIGH SPEED TOOLS

1053 Mr. White and the writer stated in our patent that molybdenum can be substituted for tungsten in modern high speed tools, and that one part of molybdenum will produce approximately the same effect as two parts of tungsten. We also stated that molybdenum is not as satisfactory an element as tungsten to use in high speed tools. The writer would repeat these assertions as giving our views at the present day upon the use of molybdenum in high speed steels.

1054 By referring on Folder 21, Table 129, under the head of "Molybdenum substituted for tungsten" to the tools Nos. 55 (at the top of the list), to 63 inclusive (at the bottom of the list), it will be noted that, particularly in the case of tools Nos. 43, 54, 50, and 61, molybdenum tools having high cutting speeds were experimented with during the development of the Taylor-White process, and that from 4 per cent to 4½ per cent of molybdenum appeared to be a sufficient quantity to make a high speed tool; whereas about 8 per cent of tungsten was required for this purpose. However, by noting our remarks made after most of these tools, it will be seen that they were brittle, had a tendency to fire crack, were weak in the body of the tool, or else they were irregular in their cutting speeds. All of these faults are most serious in their nature, and they were at that time and are still regarded by us as so serious that when a tool clearly develops any one of these troubles we at once cease experimenting with it as not worthy of consideration among first-class tools.

1055 The irregularity in molybdenum tools constitutes perhaps its most characteristic feature. By irregularity we mean that tools of the same chemical composition, and apparently treated alike, give large variations in cutting speed. We have as yet been unable to determine with certainty the cause for the irregularity existing in molybdenum tools. One explanation, however, for this trouble may lie in the fact that molybdenum tools appear to run at their highest cutting speeds when given a high heat slightly lower than the high heat required to produce a first-class tungsten-chromium tool. It may be that when the molybdenum tool is heated beyond that precise high heat which is necessary to make a first-class tool, it deteriorates.

1056 One of the most useful characteristics in the modern tungsten-chromium high speed tool is that it requires little or no skill on the part of the blacksmith to heat it up close to the melting point, and that the tool itself shows clearly by its appearance when its high heat has been reached. Moreover, it is impossible to injure the cutting

properties of these tools even if they are heated to a point at which the thinner or sharper edges begin to melt. The difficulty of judging by the eye an exact high temperature reached by a tool when close to or at its melting point is so great that if a definite treating temperature were required at these very high heats,—that is, if tools were injured by heating beyond this temperature,—much of the value of the high speed tools would be lost.

1057 Now, as stated, it appears likely that the irregularity in molybdenum tools may be largely due to the fact that a more accurate degree of high heat, considerably below their melting point, is required for them, and that this temperature must be closely judged by the eye of the smith, while no accurate judgment is required for the tungsten-chromium tools, because the tools themselves show when they are close to the melting point; and close to or at the melting point is the temperature which produces a tool giving the highest cutting speeds.

BEST MODERN HIGH SPEED TOOLS COMPARED WITH ORIGINAL HIGH SPEED TOOLS DEVELOPED BY US

1058 It will be a matter of interest to compare the various properties and chemical compositions of high speed tools as developed by us at the time that our patent was written with those of the best of the high speed tools that have been made up to the present time. Tools Nos. 26 and 27, Folder 21, Table 129, are those recommended in our patent. By referring to their speeds in cutting, on the one hand, a medium steel, and on the other hand, very hard steel and hard cast iron, it will be seen that tool No. 26 gave the higher cutting speeds on hard steel and cast iron, while tool No. 27 gave the higher cutting speeds upon medium and soft steels. Thus, at the time of the writing of our patent, in order that a machine shop should have the best tool equipment it was necessary that tools made of two different chemical compositions be maintained as standards.

1059 Referring now to tool No. 1 the best high speed tool experimented with by us in 1906, it will be noted that it has a higher cutting speed upon all the qualities of metal experimented with than any other tool. One of the gains, then, made by the latest high speed tools lies in the fact that in one tool steel are combined all of the most desirable properties, and therefore only one need be adopted in a shop as standard.

1060 We have referred in paragraphs 965 to 968 to red hardness as the distinctive property of modern high speed tools, and on Folder

3, Fig. 18, we show a photograph of a tool possessing in a high degree red hardness, while at the same time it is so soft that it has been readily filed after running successfully at very high speed. Now while red hardness is the most important property or quality sought for in high speed tools nevertheless, for certain classes of work, namely, turning the very hard qualities of steel and also hard cast iron, the property of hardness is desirable in addition to that of red hardness. The principal difference between tools Nos. 26 and 27 is that the former combines the quality of red hardness with hardness, while the latter lacks somewhat the quality of hardness, although it possesses red hardness in a higher degree than No. 26. The reason, then, that No. 26 cuts hard steel and hard cast iron at so much higher cutting speed than No. 27 is due to the fact that it adds the quality of hardness to that of red hardness. It must be borne in mind, however, that in the average machine shop more than nine-tenths of the work is done upon the medium or softer qualities of metal. Therefore, it is only upon a comparatively small class of work that the quality of great hardness needs to be added to that of red hardness in high speed tools.

1061 One property in which tools Nos. 26 and 27 were both lacking was that, athough in cutting soft metals they made the same proportionate gains in cutting speed when taking the fine feeds as when taking the coarser feeds, still when these tools were cutting steel of even medium hardness, but slightly higher cutting speed could be used with a feed finer than $\frac{1}{16}$ inch than could be taken with a feed of $\frac{1}{16}$ inch. This presented a really serious defect in our high speed tools because the greater portion of the feeds taken in the machine shops are finer than $\frac{1}{16}$ inch.

1062 As referred to in paragraphs 816 to 828, tools of chemical composition of No. 1 were proved in our recent experiments (1906) to be capable of making the same proportionate gain in cutting very hard metals with fine feeds as they made when cutting soft metals with fine feeds. This then represents a second feature in which the latest high speed tools are better than those originally developed; and this property is also due to the fact that the latest tool possesses a high degree of hardness in addition to its very extraordinary degree of red hardness. In the quality of hardness, however, it will be noted that tool No. 1 does not outstrip its nearest competitors to the same extent as it does in its extraordinary quality of red hardness, the gain in cutting medium steel being proportionally larger than the gain in cutting hard metals.

1063 The third feature in which tool No. 1 is superior to tools No. 26 and 27 is that it is stronger in the body.

1064 By far the most important improvement, however, in No. 1 tool over the original tools Nos. 26 and 27 (a matter which the writer looks upon as of even greater importance than the 50 per cent increase in cutting speed) is the fact that it is much more difficult to injure No. 1 tool through carelessness in heating upon the grindstone or through overheating in the lathe under the cut than the original high speed tools. The No. 1 tool will stand a surprising amount of overheating on the grindstone without very serious deterioration; whereas Nos. 26 and 27 were exceedingly sensitive to this bad treatment, and perhaps to this cause more than any other is to be attributed the great lack of uniformity in high speed tools which existed in the early years of their adoption. For this reason, then, No. 1 tool marks a most important advance in maintaining the all important quality of uniformity.

1065 In our patent and in writing this paper we have referred to the good effects resulting from the second or low heat treatment. The percentage of increase in cutting speed due to the second or low heat treatment was more marked in the case of our original high speed tools Nos. 26 and 27 (Folder 21, Table 139) than it is in the case of our latest high speed tool, No. 1 (Folder 20, Table 138). With the original high speed tools in many cases our low heat or second treatment resulted in a gain in cutting speed of as much as 30 per cent while in tools of the type of No. 1, the second treatment rarely resulted in a gain of more than 10 per cent and frequently even not so large a percentage as this.

1066 On the whole, we look upon this as a very great improvement in the latest high speed tools over the original, because even if the new tools are not given the second or low heat treatment at all, still they will be far more nearly uniform than the original tools of this class. Moreover, among those who have stolen and who are using the process of making high speed tools, by heating tools close to their melting point but very few have used in the past or are now using the second or low heat treatment except in as far as this treatment is given to the tool through heating it incidentally or accidentally upon the grindstone or through heating it under the pressure of the chip in the lathe. The only feature in which tool No. 1 is less desirable than tools Nos. 26 and 27 is that it is more difficult to forge, at the old forging heats, namely about a light cherry red.

1067 We have already pointed out that the substitution of chromium for manganese in both the old self-hardening steels and in the high speed steels allows the tool to be forged at a heat very considerably higher than the light cherry red without danger of crumbling. In other words, the addition of the chromium and the absence of

manganese render the tool just the opposite of what is called "red short"; that is, just the opposite of a liability to crumble when struck with a hammer at a high heat.

1068 It will be noted that tool No. 1 contains from 5½ per cent to 6 per cent of chromium, and this increased percentage of chromium has the very useful effect of allowing the tool to be forged at an exceedingly high heat, in fact, not very far below the melting point. The danger of injuring the tool through oxidization at this extremely high heat is great, however, and we therefore recommend as a forging temperature a light yellow heat. When tools containing from 5½ per cent to 6 per cent of chromium and of the general chemical composition of No. 1 tool are heated to this light yellow heat they are much easier to forge even than the original high speed tools, Nos. 26 and 27, and also easier to forge than such of the tools as lie between Nos. 2 and 23, and which contain less than 5 per cent of chromium. This is an added and a great advantage of No. 1 tool over the other modern high speed tools.

1069 Tools of the composition of No. 1, then, should be forged at a light yellow heat.

1070 To recapitulate, the improvement in the latest high speed tools over the original high speed tool consists in:

1071 (A) Far greater uniformity, owing to less danger in being injured in grinding and in daily use.

1072 (B) 50 per cent increase in cutting speed.

1073 (C) The attainment of almost its maximum cutting speed without the necessity of the second or low heat treatment.

1074 (D) The combination in the same tool of the highest degree of red hardness with a high degree of hardness, thus requiring only one standard high speed tool steel in the shop.

1075 (E) The ability, owing to increased hardness, coupled with the necessary red hardness, to make the same proportionate gain when cutting with fine feeds upon hard metals as upon soft.

1076 (F) Greater strength in the body.

1077 The only point of inferiority is increased difficulty in forging at a cherry red, and if blacksmiths are taught to forge their tools at a light yellow heat, these tools are easier to forge than the original high speed tools.

1078 In paragraph 973 we have referred to the fact that since writing our patent no improvement whatever has been made in the heat treatment of high speed lathe and planer tools. The all-round gain in the No. 1 tool (Folder 20, Table 138) over the original high speed tool, then, lies entirely in a change in chemical composition.

It would seem therefore a matter of interest to point out the change in the composition of these tools, and, so far as practicable, to indicate the cause and effect of the change in each of the improved elements.

PRINCIPAL CHEMICAL CHANGES MADE IN BEST MODERN HIGH SPEED TOOL OVER ORIGINAL HIGH SPEED TOOL DEVELOPED BY MESSRS. TAYLOR AND WHITE

1079 Our patent, describing the original high speed tool, claims, briefly speaking, the combination of one-half of one per cent of chromium, or more, with one per cent of tungsten, or more; the tool to be treated to the high heat, etc. In our patent we also state that, practically speaking, the best tools developed by us at that time contained 2.00 per cent to 3.80 per cent of chromium instead of 0.5 per cent of chromium, and 8.00 to 8.50 per cent of tungsten instead of 1.00 per cent of tungsten.

1080 The principal chemical change which has taken place in the best high speed tools up to the present time has been to still further increase the percentage of chromium, so that instead of containing 3.80 per cent as recommended by us, the tools now contain from 5.50 per cent to 6 per cent and to still further increase the tungsten from 8.50 per cent to from 18.0 per cent to 19.0 per cent. This large increase in the percentage of chromium and tungsten has produced the material increase of 50 per cent in the red hardness of the tool and at the same time, also, a material increase in the hardness over our original high speed tool No. 27. It is notable, however, that if the percentage of tungsten is increased much beyond 19.0 per cent even although the chromium is also increased in quantity, that the tool diminishes in red hardness. This fact will be noted by comparing the cutting speeds of No. 14 tool (which contains 24.64 per cent of tungsten and 7.02 per cent of chromium) with the cutting speed and chemical composition of No. 1 tool; and the metal close to the cutting edges of tools containing these very large percentages of tungsten and chromium appear to yield, or become slightly deformed, particularly when cutting the thinner shavings or chips.

1081 The presence of high manganese in a tool and also the presence of high carbon, both tend to increase the hardness of the tool. They make the tool more brittle in the body; and in addition, high manganese causes the tool to crumble in forging when heated much beyond a bright cherry red. It was for this reason that we, in our original Taylor-White tools, specified low manganese (0.15 per cent); and this has been adopted as a characteristic in all the modern high speed tools.

1082 The tools as recommended in our patent contained carbon to the extent of 1.85 per cent, and this element has been lowered in modern high speed tools largely as a result of the fact pointed out by us in our patent, that the quality of red hardness is not materially affected by either high carbon or carbon as low as 0.86 per cent. If either high manganese or high carbon (as much as 1.85 per cent) were used in a tool in combination with 5½ per cent of chromium and 19.0 per cent of tungsten, the tool would be brittle in the body and exceedingly difficult to forge; and the presence of high manganese particularly would tend to reduce rather than to increase its red hardness. Therefore, the latest high speed tools contain manganese in as small quantities as is practicable when the expense of the mixture and the needs in melting are considered.

1083 Modern high speed tools have been recently experimented with by us containing carbon varying from the small amount of 0.32 per cent to the higher percentage of 1.28; and our conclusion from these experiments is that the property of "red hardness" in the modern high speed tools is not noticeably affected by either high or low carbon within these limits. The quality of hardness, however, in the tool is affected by the percentage of carbon and, as previously explained, a certain degree of hardness is required as a property in high speed tools for several reasons.

1084 The carbon contents of the modern high speed tools, then, would seem to be governed by a compromise between the two requirements: on the one hand, higher carbon is needed to produce a greater degree of hardness in the tool; and, on the other hand, lower carbon is needed to make the tool more readily forged and also to make it stronger and tougher in the body.

1085 As indicated on Folder 20, Table 138, analysis of tool No. 1, the best tool experimented with by us contained 0.68 per cent carbon, and we recommend for a modern high speed tool not less than one-half of one per cent (0.5 per cent).

1086 There is one element of less importance than those previously considered which nevertheless should receive attention. The statement has been published several times that high silicon tended toward higher cutting speeds in high speed tools. In developing our patent, we experimented quite thoroughly with this element, and arrived at the conclusion that high silicon tended toward slower cutting speeds, particularly when cutting the harder metals. In our patent, therefore, we recommended the low silicon, 0.15 per cent, and it will be noted that, on the whole, low silicon is a characteristic of most modern high speed tools.

1087 Our experiments indicate that high phosphorus and sulphur are much less injurious to high speed tools than they were to the carbon tools. However, these elements still exert a somewhat injurious influence upon the steel, and we therefore recommend, inasmuch as the presence of chromium and tungsten in large quantities necessarily render high speed tools very expensive, that the best qualities of low phosphorus and low sulphur iron should be used in their manufacture.

DISCOVERY BY MESSRS. TAYLOR AND WHITE THAT SMALL QUANTITIES OF VANADIUM IMPROVE HIGH SPEED TOOLS

1088 No manufacturer of tool steel needs to be informed that the chemical analysis of steel (at least those analyses which are ordinarily made in our best chemical laboratories) is not alone a true or infallible guide to the real quality of steel. There are other factors than the elements which are ordinarily determined in laboratories which affect the quality of the tool steel.

1089 We all know that to obtain the best quality of tool steel, the mixture must be melted just right. The melting must be thorough and complete in order to bring about the proper alloying of the tungsten and chromium with the iron and carbon without at the same time oxidizing the bath. In addition to this, the metal must be poured or "teemed" in the right way in the molds, and the ingots must be made of the best size and shape for the subsequent operation of hammering the steel. The steel itself must be also carefully heated and handled during the operation of hammering. All of these elements affect the quality of the steel as well as the chemical composition.

1090 An examination of the tools betwen No. 1 and No. 19 on Folder 20, Table 138, will illustrate this fact; *i. e.*, that something other than the chemical composition modifies the cutting speed of these tools. This will be particularly noted by comparing the analysis of tool No. 3 with that of tool No. 5. These steels chemically resemble each other very closely, and yet No. 3 has a distinctly better cutting speed than No. 5.

1091 Perhaps the most important of these collateral elements or influences affecting the quality of tool steel, however, is that of the melting and pouring or teeming of the ingot in such a way as to remove as far as possible those chemical impurities which are not indicated by the ordinary chemical analyses; and of these impurities we believe that the more obscure oxides constitute the worst enemies of steel. The term "good melting" might be translated into more scien-

tific language by saying that the steel should be so carefully mixed and melted as to contain the minimum quantity of these injurious oxides. There have been various expedients adopted by makers of tool steel to secure this end, and some of these are still held more or less as trade secrets. It is our belief, however, that we have discovered during the last year perhaps the most efficacious remedy for "bad melting" that has yet been devised. We refer to the use of vanadium, a metal comparatively new in the art of practical steel manufacture. Mr. James M. Gledhill, in his paper on "The Development and Use of High Speed Tool Steels" published in the "Journal of the Iron and Steel Institute," in 1904 speaks of having substituted vanadium for chromium in high speed tools, and he states that while the vanadium when used in cutting a steel of medium hardness stood well, yet it did not do better than tools containing the element of chromium.

1092 Our experiments indicate the fact that vanadium should not be substituted for chromium, but that a very minute quantity of vanadium should be added to the mixture in melting, and that its use to the extent of from 0.15 per cent to 0.35 per cent is as effective as higher quantities in the mixture. Our experiments would indicate the probability that the good effects of vanadium are derived from its chemical property as a cleanser of the steel during the operation of melting rather than as a very valuable property in the steel after it is melted. From 0.15 per cent to 0.30 per cent of vanadium when mixed with the steel in the pot sometimes disappears entirely from the finished steel, and its presence cannot be found by analysis, indicating that it has probably joined with some other element or elements, and gone off into the slag. It is likely then that minute quantities of vanadium act as cleansers of the bath, uniting with some of the obscure oxides and carrying them off into the slag. We know, for example, that the shop in which No. 1 tool (Folder 20, Table 138) was made is not run with the exceptional skill of long experience, and yet in this shop the addition of small quantities of vanadium very materially improves the cutting properties of the tool.

1093 An illustration of this fact will be seen by comparing steel No. 18 with steel No. 19, these two steels being practically the same chemical composition except that one of them has had a small amount of vanadium added to it. These samples of steel were made in the melting shop above referred to.

1094 To close the subject of the chemical composition for high speed tools, we do not wish to give the impression that we believe that No. 1 tool represents the chemical composition of the best tool which will ever be made. On the contrary, we believe that the

improvement in the proper combination of the various elements required to make a high speed tool will continue, and it is a matter of surprise to us that greater improvement has not been made since our original discovery of high speed tools. Manifestly, it is highly desirable that a mixture should be found for high speed tools which shall be much more economical than any of the mixtures now used; and we believe that in the future this result will be brought about. It would seem as though this represents perhaps the most important field for the future economical development of the high speed tool.

THEORY OF HARDENING STEEL

INVESTIGATIONS MADE TO FIND AN EXPLANATION OR THEORY FOR THE PHENOMENA CONNECTED WITH "CHROMIUM TUNGSTEN" HIGH HEATED TOOLS

1095 The facts regarding the effects of heat treatment on "chromium tungsten" and "chromium molybdenum" tools have been carefully investigated, and recorded as above. As yet, however, no theory has been advanced which in the judgment of the writer explains these phenomena. Investigations were made on this subject by Otto Böhler, of Austria in 1903, and published in an article by him entitled "Wolfram und Rapid Stahl." Several articles have been written also by Messrs. Osmond and H. LeChatelier, both of whom are among the most careful and scientific investigators in the metallurgical field, and valuable data is given by Mr. J. E. Stead, in his contribution to the discussion in the Report of the Alloys Research Committee of the Institution of Mechanical Engineers; but the most thorough and up-to-date investigation which has come to the writer's attention is that made by Prof. H. C. H. Carpenter, Ph. D. of the National Physical Laboratory in England, and published in the "Journal of the Iron and Steel Institute," 1905, p. 433. In their papers on this subject all of these writers, however, assume that the reader already has a certain familiarity with the subject, and they use without definition, words and certain technical expressions and even conventional symbols which render their writings more concise and more simple but only to one who has read much that has previously been written. These special technical expressions make it difficult for even an educated engineer to clearly understand their articles without very considerable study. The present paper is intended not only for engineers familiar with the subject, but more especially for shop superintendents, managers and foremen, many of whom have but small familiarity with the

scientific or metallurgical side of the problems. The writer will, therefore, endeavor to give in simple words an explanation of some of the more important phenomena developed by these gentlemen.

1096 Carbon or tempered tools are made from tool steel containing from $\frac{75}{100}$ of 1 per cent up to about $1\frac{1}{2}$ per cent of carbon. In addition, this class of tool steel contains small quantities of silicon, manganese and, unfortunately, phosphorus, and sulphur. The hardness of tools made from this class of steel, however, depends mainly upon the carbon, and carbon exists in tools, broadly speaking, in two conditions or states; one of which may be called the *hardening carbon* and the other the *softening carbon*. The technical names given to these two conditions being cementite and pearlite, a bar of this carbon tool steel as it is received from the maker contains carbon practically all in the softening state. After the tool is forged to shape, in order to harden it, as is well known, it must be heated above a certain definite temperature. This temperature varies according to the amount of carbon, manganese and silicon which are present in the tool steel; but, in general, it is fairly close to 1450 degrees Fahr. (786 degrees C.). When these tools are heated slightly beyond 1450 degrees Fahr. (786 degrees C.) the softening carbon is changed entirely into hardening carbon, and it takes a certain interval of time for this change in the form of the carbon to take place. If the tool is then cooled slowly until it is below 1400 degrees Fahr. (760 degrees C.) the form of the carbon is again changed back from hardening to softening carbon. This change backwards and forwards from hardening to softening carbon, or vice versa will take place each time the tool is heated above 1450 degrees Fahr. (786 degrees C.) or cooled below 1400 degrees. Fahr. (760 degrees C.)

1097 It is doubtless due to the fact that the transformation from the hardening form to the softening form of carbon requires a certain quite appreciable length of time that carbon steel tools can be hardened at all. If tools are heated above 1450 degrees Fahr. (786 degrees C.) and are plunged into cold water, or very rapidly and continuously cooled in any other way, until they arrive at a temperature below about 392 degrees Fahr. (200 degrees C.), at no one period in the process of cooling is time enough allowed for the hardening carbon to change its form into softening carbon, and after the temperature of the tool is below 392 degrees Fahr. (200 degrees C.) the hardening carbon is imprisoned, as it were, in its hard or diamond-like form in the tool, and gives to the whole tool its hardness; and as long as a tool remains below 392 degrees Fahr. (200 degrees C.) the change from hardening back to softening carbon cannot take place. If the process of cooling

a carbon steel is halted, however, at any point between the temperature of 1400 degrees Fahr. (760 degrees C.) and that of 392 degrees Fahr. (200 degrees C.) even for a comparatively short time, then to a greater or less degree, the change from hardening to softening carbon will take place.

1098 Tools which have been hardened by sudden quenching from 1450 degrees Fahr. (786 degrees C.) are in most cases too brittle for practical shop use, and they are softened or "tempered" to any desired degree by reheating them above the temperature of 392 degrees Fahr. (200 degrees C.) The higher the tool is heated above this point up to about 600 degrees Fahr. (315 degrees C.) the softer and softer it becomes as the hardening carbon is gradually changed back into softening until at 600 degrees Fahr. (315 degrees C.) it is entirely soft.

1099 Mr. LeChatelier invented an exceedingly sensitive and accurate pyrometer for rapidly measuring the heat at higher temperatures, and investigations made a number of years ago with this pyrometer demonstrated the fact that as the carbon is changed from its hardening to its softening form, so definite and powerful a molecular action or change in the internal structure takes place inside the steel as to actually develop a very considerable amount of heat. Therefore, as a tool which has been heated hot enough to contain carbon in the hardening form is gradually cooled when it reaches the critical temperature 1400 degrees Fahr. (760 degrees C.) at which this internal molecular change occurs, the heat brought about by this molecular disturbance is actually sufficient in many cases not only to entirely stop for a considerable length of time the cooling of the tool, but to slightly reheat the tool; and it is for this reason that this point of carbon transformation from hardening to cooling and vice versa has come to be called the "reheating point" the "point of recalescence" or the "critical point" in the tool steel. The heat which is developed by this molecular change, however, is not always sufficiently great to actually reheat the steel to a higher temperature, although in all cases it checks and temporarily slows down the rate of cooling. For this reason this change point in the carbon is more frequently called the "critical point," and this would appear to be, on the whole, a better name.

1100 All tool steels, whether of simple carbon or of the later high speed varieties, have at least one critical point, and many of them two or more critical points, in cooling down from a high heat to the normal temperature of the air; and it must be remembered that in each case these critical points shown by the cooling experiments indicate that some internal molecular change has taken place. In heating carbon

tool steel the lower critical point is, generally speaking, between 392 Fahr. (200 degrees C.) and 600 degrees Fahr. (315 degrees C.) at which point softening or tempering is taking place. And the upper critical point, as before explained, occurs at about 1450 degrees Fahr. (786 degrees C.), at which point softening carbon is changed back into hardening carbon. The critical points in heating tool steel, however, do not occur at the same temperature as those for cooling, showing that the internal chemical or molecular changes in the carbon or other ingredients do not occur at the same temperature while the heat is going upward as they do while the heat is going downward. (See Folder 10, Figs. 57 and 58.

1101 By comparing the critical points, Folder 10, Figs. 57 and 58, in the heating curves shown at the right hand side of the vertical line with the critical points of the cooling curves on the left hand side, it will be noted that the principal critical point in heating is higher by about 160 degrees Fahr. than the principal critical point in cooling. The operator who is hardening carbon steel, therefore, is much more interested in the heating than in the cooling curve, as it is to the former that he looks to find the critical point just above which he must heat his tool in order that it may harden thoroughly, preserve a fine grain, and be free from the brittleness and various troubles which come from overheating.

1102 All of the theorists who write upon this subject practically agree that the hardness of old fashioned self-hardening tools is due primarily or principally to the presence of carbon in the steels (that if carbon were removed from self-hardening steels they would not be much if any harder than carbon tool steel would be if the carbon were removed from it); namely, that without carbon all qualities of steel would be soft so far as metal cutting properties are concerned.

1103 We have just pointed out that carbon (in ordinary tool steel) which exists in the "hardening" condition when the steel is heated above the critical point changes in an exceedingly short time to carbon in the "softening" condition after the tool is cooled below the critical point. A few seconds or minutes, depending upon the size of piece, are sufficient time for the change from hardening to softening carbon to take place in ordinary carbon steel tools.

1104 The theory explaining why the old fashioned self-hardening tools have their property of hardness is that when these tools are heated up to above the critical point and the carbon is formed into the "hardening" state, and they are then cooled below the critical point, the hardening carbon instead of changing quickly to softening carbon (as in ordinary tool steel) becomes tangled, as it were, with the tungsten

and manganese, and takes many hours to change from the "hardening" to the "softening" state, instead of a few seconds or minutes, as with ordinary tool steel when tungsten and manganese are not present to any large extent.

1105 A tool, however, after being forged, even if laid down in the air to cool, will cool down to a black heat in a few minutes at most; so that with self-hardening tools in practical, everyday conditions, there is never sufficient time, owing to the tangling or retarding effect of tungsten and manganese, for the carbon to change from the hardening to the softening condition.

1106 We believe that this theory is substantially correct as far as the quality of "hardness" is concerned, but as we shall point out later, it does not at all account for or explain the new property of "red hardness" which is the characteristic of high speed tools. And so far as we know, theoretical writers on the subject have up to this time confused these two properties, speaking of the new property of "red hardness" as though it were the same as "hardness."

1107 Most modern scientific articles which have been written on the hardening and the tempering or softening of steel tools treat mainly of two subjects:

a the crystalline or other structure of the steel, as affected by heat treatment and chemical composition, and as revealed by polishing, etching with acid and examining with a microscope; and

b a study of the critical temperatures just referred to, and of the very evident connection of these critical points with the powerful internal changes in the quality, condition or formation of the carbon which causes the tool to be hard in one case and soft in another.

1108 A clear understanding of the effect of these critical points upon hardening is helped by diagrams showing them graphically.

1109 If paper be ruled with horizontal lines at equal distances apart which represent increases in temperature, say of 100 degrees each, and if upon paper ruled in this manner a line be drawn consisting of a series of dots which are spaced at distances one from another, corresponding to the rapidity with which the temperature of the steel falls as it is cooled; when the critical points in the cooling are reached, the cooling curve will be bent sharply either to the right or to the left, forming a very definite and clearly visible break or sharp deflection from the general line of the curve, and in this way the exact location of the remarkable changes in the carbon of the steel from hardening to softening carbon, etc., becomes clearly visible at a glance.

1110 In the diagram, Folder 10, Fig. 56, is shown a set of these curves which represent the critical points in cooling and heating steel of the chemical composition of ordinary carbon or tempering tool steel, and in the diagrams, Folder 10, Figs. 57 and 58, are shown cooling and heating diagrams of the modern high speed tools. Fig. 56 was sent to the writer through the kindness of Prof. H. C. H. Carpenter, and Figs. 57 and 58 are reproduced from Professor Carpenter's paper above referred to. These diagrams represent the best work of this character which has as yet come to the attention of the writer.

1111 On Folder 10, Fig. 57 (Alloy 14), and Folder 10, Fig. 58 (Alloy 16), is represented the cooling of two different modern high speed tool steels of the following chemical compositions respectively:

FIG. 57

Carbon	0.85 per cent
Chromium	3.0 per cent
Tungsten	12.5 per cent

FIG. 58

Carbon	0.55 per cent
Chromium	3.5 per cent
Tungsten	13.5 per cent

1112 The curves on the left-hand side of the vertical line represent the cooling curves, those on the right-hand side represent the heating curves. The five curves on the left-hand side represent the cooling of the steel after it has been heated to 1652 degrees Fahr. (900 degrees C.), 1832 degrees Fahr. (1000 degrees C.), 2012 degrees Fahr. (1100 degrees C.) and 2192 degrees Fahr. (1200 degrees C.), respectively, and in all of these curves sharp bends to the right which begin to occur at from about 1364 degrees Fahr. (740 degrees C.) to 1324 degrees Fahr. (718 degrees C.), indicate very clearly the critical points at which some powerful molecular change occurred during the process of cooling.

1113 Mr. White and the writer, during the orginal development of modern high speed tools by us, accurately heated chromium-tungsten tools of standard shapes, one set after another, to different temperatures, and then determined their standard cutting speeds, as described in paragraphs 106 to 109. This accurate practical heating and running of the tools (without any theory on our part as to the chemical or molecular causes which produced the extraordinary phenomena) led to the discovery that marked improvements in the cutting speed of chromium-tungsten steel were attained by heating the tools from a temperature of 1725 degrees Fahr. (958 degrees C.) up close to the

melting point; the higher the point to which the tools were heated, the greater was the cutting speed attained.

1114 By referring to the several curves, it will be noted that in the 1652 degrees Fahr. (900 degrees C.) curve (on the extreme left of the diagram) which is below the point (1725 degrees Fahr.) at which high heating begins to make large improvements in the cutting speed, there is much greater deflection or internal chemical change when the critical point is reached in cooling the tool than in the curves of those tools which were heated to the higher temperatures, and that particularly in the diagram (Alloy 16), Folder 10, Fig. 58, the higher the tool is heated, the smaller becomes the sharp bending of the curve to the right, and therefore the smaller becomes the molecular action or change in cooling down the tool at the 1332 degrees Fahr. (722 degrees C.) critical point.

1115 It would seem logical, therefore, to infer that there is some connection between the increase in the cutting speeds of these tools as they are heated higher and higher, and the diminution in the molecular action at the 1364 degrees Fahr. (740 degrees C.) and 1324 degrees Fahr. (718 degrees C.) critical points. Yet it must be remembered that "high speed" tools possess the two distinct properties of "hardness" and "red hardness" and that the high heating (in the case of chromium-tungsten tools) progressively improves both of these qualities; therefore our experiments and observations have led us to the conclusion that these heating and cooling diagrams are valuable chiefly in their relation to the quality of "hardness," not in their relation to "red hardness." Our reasons for this will be given later in paragraphs 1119 to 1123.

1116 Curves or diagrams of the type shown in Figs. 57 and 58, however, throw no light upon the important question as to the exact heat at which the tempering or softening of the high speed tool begins, or as to what range of temperatures this softening process extends over. After writing his interesting paper, above referred to, Professor Carpenter made another investigation, the results of which were published under the title of "Tempering and Cutting of High Speed Steels" in the "Journal of the Iron and Steel Institute," July, 1906, for the purpose of determining the range of the temperatures at which tempering or softening of high speed tools begins, and the range of temperatures through which softening extends and is finally completed. In this investigation he used the first method of scientific investigation above referred to in paragraph 1107 (A); namely, the microscopic structure of the steel. On Folder 4, we reproduce one of his plates illustrating the typical structure of high

speed steels proceeding from its hardest to its softest state, and we quote Professor Carpenter's discussion[1] of these plates, making extracts from pages 4 and 5 of his paper:

1117 "Characteristic structures of the hardened and fully tempered or softened alloys are shown on Folder 4, Figs. 19a and 19e. Fig. 19a consists of white polyhedral crystals, and Fig. 19e of small white crystals embedded in a darkly etching matrix. The difference between the two types of structure is very characteristic, and the progress of tempering can be followed readily by microscopic examination. . . . No tempering occurs below 550 degrees C. At this temperature the structure seen on Figs. 19b and 19c is obtained. The white areas represent untempered material, the colored areas parts where tempering has begun. Tempering starts from a series of centers, and gradually invades the rest of the material. Photomicrograph, Folder 4, Fig. 19c, shows that the incipiently tempered material consists of a mixture of lightly colored polyhedra, needles, and a darkly colored matrix. At 600 degrees C. the white polyhedra disappear, and the structure consists of a fairly uniformly colored, ill-defined granular mass from which all evidence of polyhedra is absent. The dark patches probably represent the centers from which tempering proceeded (see Folder 4, Fig. 19d). At 650 degrees small white crystals make their appearance, but they do not attain their proper proportion, corresponding to fully tempered material, until after treatment at 700 degrees C. Thus in the case of this alloy tempering was structurally detected at 550 degrees under the conditions of experiment chosen, but was not complete till 700 degrees."

1118 In reading the above quotation it should be borne in mind that Professor Carpenter used the word "tempering" in the sense of progressive softening, or what is commonly called by blacksmiths in the case of ordinary carbon tools "drawing the temper."

1119 Professor Carpenter made elaborate tempering or softening experiments at accurate temperatures upon nine different alloys, some of which represented the best modern high speed tools at that time available, while others represented steels more or less approximating to the best high speed tools. In the course of this investigation it appeared that one of these alloys of the following chemical composition required to soften it materially higher temperatures than any of the others.

[1] In this quotation we use of course our own folder and figure numbers in the place of those used by Professor Carpenter.

	Dr. Mathews' Steel.	
	No. 8	No. 8 b
Carbon	0.47	0.430
Silicon	0.15	0.048
Sulphur	low	0.012
Phosphorus	low	0.022
Manganese	0.1 to 0.2	0.172
Chromium	2.99	3.103
Molybdenum	4.29	4.172

The etched specimens examined with the microscope showed that this alloy began to distinctly soften at a higher temperature than any of the others, and was not completely softened even at 930 degrees C., while the others were completely softened at about 700 degrees C. In view of this very high softening point for this particular steel, Professor Carpenter had cutting tools made from steel very closely resembling those of the analysis shown in column No. 8b, and these tools were run in competition with high speed tools in general similar in composition to the following:

Carbon	0.55 per cent
Chromium	3.5 per cent
Tungsten	13.5 per cent

1120 The result of these practical speed tests with tools showed that the steel which resisted tempering or softening at the high heat of 800 to 930 degrees C. was far inferior in cutting properties to the high speed steel which was completely softened at about 700 degrees C.

1121 This experiment, which was very thoroughly conducted, shows conclusively that this second scientific method of investigation fails in attempting to establish any practical relation between the cutting properties of high speed tools and their microscopic structure and this conclusion agrees exactly with that arrived at by Mr. White and the writer in our original investigation in developing the high speed tool. We found, as stated in our patent, that many high speed tools contain austenite, a structure only to be produced by excessively high heats and indicative of great hardness. We also found in our microscopic examination other structures somewhat similar to those illustrated by Professor Carpenter. Although our examination in this direction was far from being as thorough as that of Professor Carpenter, we went far enough to completely satisfy ourselves that there was no traceable relation between the highest cutting speeds and any particular one of the microscopic structures. We examined sev-

eral high speed tools which showed equal cutting properties and yet whose microscopic structure differed very materially

1122 Professor Carpenter has traced the relation between these microscopic structures and the "hardness" of the tools, and we have no doubt that in this investigation,—as well as in his former investigation showing the relation between the cooling curves and the "hardness" of the steel,—that he is correct; but like all the other scientific writers on this subject whose works have come to our attention, he has failed to recognize the existence of "red hardness" as a property of these steels entirely independent of hardness. We would again call attention to the fact that the highest degree of "red hardness" can be found in these high speed tools when accompanied either by the *highest* degree of *hardness*, on the one hand, or by a very *considerable degree* of *softness*, on the other hand. And we repeat most emphatically that hardness in high speed tools is in no sense a guide to their high speed qualities which depend mainly upon the quality of red hardness. As illustrating this fact, we refer again to the photograph, Folder 3, Fig. 18, which shows a high speed tool with deep nicks which were readily filed in it with an ordinary carbon steel file after it had run successfully at high speed. It is also a fact that the No. 1 tool, Folder 20, Table 138, which when properly treated represents the best all-round modern high speed tool for cutting metals of all qualities experimented with is not a particularly hard tool. It is less hard, for example, than the old fashioned Mushet tools, and far less hard than almost all of the high speed tools alloyed with molybdenum. It can be filed with a hard carbon steel file, and yet, in spite of being only moderately hard, it possesses the very highest degree of red hardness.

1123 We would also call attention to the fact that in Profesor Carpenter's description of the photographs of the steel structures illustrated on Folder 4, he states that softening has proceeded so far at the temperature of 1022 degrees Fahr. as to change the hard structure shown in Fig. 19a to the distinctly softer structure shown in Fig. 19c. It will be remembered that paragraphs 991 to 993 state that the very best high speed tools were produced by reheating the tool to a temperature of 1150 degrees Fahr. This was done for the purpose of imparting the very highest degree of red hardness to the tool. It is clear, then, that if softening has progressed, as shown in Professor Carpenter's paper, very materially at a temperature of 1022 degrees Fahr. and if, on the other hand, the highest degree of red hardness is imparted to the tool by reheating it to at least 1150 degrees Fahr., there is not only a great difference between the qualities of "hardness" and

"red hardness," but also that these two qualities are not affected to the same temperatures.

1124 Before accepting a theory in any particular case, the facts should be thoroughly established and verified, and the theory if correct should thoroughly account for all of the known facts.

1125 It is clear that as to high speed cutting tools the most important facts are best established by carefully heating the tools to known temperatures and then running them in standard speed tests under uniform conditions in cutting uniform metals, as described in paragraphs 137 to 148. This method of determining the qualities of cutting tools may be briefly called the method of "heating and running" the tools; and this, as already explained, was the method originally adopted by us in developing the high speed tools for arriving at all of the important facts then developed. Of these facts the most important are:

a how to produce tools having the greatest red hardness, that is, tools which will run at the highest standard cutting speeds on different qualities of metal; and

b the determination of at what temperatures and in what manner the quality of red hardness in the high speed tools is impaired or broken down.

1126 As we have already stated in our description of the experiments tried by us during the summer and fall of 1906, it is an extraordinary fact that the heat treatment originally developed by us through this method of "heating and running" the tool still continues to produce a greater amount of red hardness and higher cutting speeds than any heat treatment since devised. We have not, however, since the original development of high speed tools in 1898 investigated by the method of "heating and running" the second important fact, namely, at what temperature the quality of red hardness in the higher chromium and tungsten tools begins to be impaired. It may be that the best recently developed high speed tools will hold their quality of red hardness at higher heats than those determined by us, and it is of great importance that this subject should again be thoroughly investigated by the sure, though slow and expensive, method of heating and running.

1127 Our original investigations showed that red hardness was impaired by heating tools above 1200 degrees Fahr., and that the quality of red hardness was entirely removed by heating them up to 1350 degrees Fahr. and holding at that temperature for any length of time. Now, it will be noted that in the heating curves shown by Professor Carpenter, no critical point is shown at these temperatures,

which are the critical temperatures so far as we know for high speed steels and therefore the critical temperatures affecting red hardness. Professor Carpenter's recent microscopic investigations on the structure of steels and the temperatures affecting this structure show radical structural changes beginning at below 1022 degrees Fahr., and extending up to 1292 degrees Fahr. It will be noted that the range of temperatures corresponding to these structural changes with which Professor Carpenter has connected the quality of hardness in steels differs entirely from the range of temperatures which we found were intimately connected with the destruction or deterioration of red hardness. Now, the temperatures which impair red hardness in the latest high speed tool steels are without doubt as high or even higher than those which impaired red hardness in our original tools. All of these facts indicate clearly that the two methods as yet devised by scientists for determining the most important quality in the new high speed steels are ineffective.

And when we consider all of the facts, it is a matter of doubt whether in producing the quality of "red hardness" in tools, carbon plays the all-important part that it does in the quality of hardness. It may be questioned whether red hardness is not more intimately connected with chromium, tungsten and molybdenum in their heat treatment than with carbon.

1128 We do not wish to discourage the type of investigation undertaken by Professor Carpenter and Messrs. Osmond and LeChatelier. On the contrary, we believe it of very great importance to find, if possible, some simpler index or guide than is now known, to the cutting properties of high speed tools, namely, some guide or index that is simpler than making elaborate standard cutting speed tests with carefully standardized tools upon standardized forgings. This test requires so much expensive apparatus, consumes so much time, and is so slow, that a simpler index or guide which will indicate correctly the quality of high speed tools is much needed. Moreover, we firmly believe that in time some simpler index to the property of "red hardness" in tools will be found.

QUALITY OF METAL BEING CUT

THE EFFECT OF THE QUALITY OF THE METAL BEING CUT UPON CUTTING SPEED

1129 Although we have given a large amount of study and made great numbers of experiments upon the effect of the quality of the metal being cut upon the cutting speed, yet we have met with less success in reducing this subject to a scientific basis than in the case of any other of the elements affecting the cutting speed of tools. In the present state of the art, at least so far as our knowledge of it extends, it is impossible to predict with accuracy the exact hardness (or more properly speaking, the effect of the quality of the metal upon the cutting speed) of the various forgings and castings which are worked upon in a machine shop doing a large variety of work.

1130 However, while this element of the problem presents great difficulties, still in the various machine shops which we have systematized we have always sooner or later succeeded in training the man who with the slide rule directs the speed of the machines so that he is enabled to predict with a fair degree of accuracy the hardness of the great bulk of the materials which are machined in the shop. This involves not only a careful study of the general data which we have obtained on this subject, but also a long and detailed study of the average hardness of the particular set of forgings and castings which the shop deals with.

1131 We would emphasize the fact that this study can only be made and the very useful knowledge which it supplies can only be attained through a careful investigation of the hardness of the individual forgings and castings as they are from time to time found in the shops. Such an investigation frequently results in a temporary delay in turning out the work in hand, and while it takes place, is of inconvenience to the general running of the shop and is expensive both in time and money. However, the final results obtained from such careful study are of the greatest value, and assistance in increasing the output of the shop.

1132 In well-managed shops the collateral advantages which result from these experiments are also great. With the attention of the superintendent of the shop is brought to the irregularity in the quality of the various forgings and castings which are machined, if he is a man of the proper caliber, he takes steps to see that his castings and forgings are purchased upon carefully written specifications so as to establish a greater degree of uniformity; and this generally results both in a better quality of forgings and castings and also in materials

which can be machined at higher cutting speeds. On the other hand, the type of superintendent or foreman is very frequently met with who can see nothing but the difficulties of obtaining sufficiently accurate data to enable the slide rule man to properly do his work, and such men are generally so firmly convinced that no good can come of the whole scheme of attempting to lay out tasks for workmen, that the company having a superintendent of this type had better either use some other scheme of management than ours or get another superintendent.

SYSTEMATIC CLASSIFICATION OF STEEL FORGINGS AND CASTINGS ACCORDING TO THEIR CUTTING SPEEDS

1133 For practical use in the machine shop it is evident that the most important and logical method of classifying all forgings and castings which are to be machined is in accordance with their cutting speeds.

1134 The man who operates the slide rules and assigns the proper cutting speeds for the machines is interested only in the quality of the forgings as far as it affects their cutting speeds. We have, therefore, divided all metals into classes according to their cutting speeds, which vary from one another with the common ratio of 1.1, namely:

Class No. 1 corresponds to that metal which will give us the highest cutting speed which we are likely ever to use in a machine shop;

Class No. 2 represents a metal whose cutting speed is that of Class No. 1 divided by 1.1, or

$$\frac{\text{Cutting speed of Class 1}}{1.1}$$

and so on, the cutting speed of each class being connected with the one preceding it by the ratio of 1.1.

1135 It is of great importance to connect this numerical scale of hardness (which varies by the common rate of 1.1) directly and permanently with certain qualities of metal and with cutting tools of definitely known cutting properties. As a basis for accomplishing this we would state that Class No. 13 upon this scale corresponds to a cutting speed of 60 feet per minute, for a standard cut of 20 minutes duration when a high speed $\frac{7}{8}$ inch tool (see Folder 5, Fig. 24) of the chemical composition of tool No. 27 (Folder 21) is used, taking a depth of cut of $\frac{3}{16}$ inch and feed of $\frac{1}{16}$ inch.

1136 Our experiments indicate also that Class No. 13 represents a speed of 99 feet (in round numbers 100 feet) for the best high speed

tool (Folder 20, Tool No. 1), running under the same conditions as stated in paragraph 744.

1137 Using this data as a basis, our scale of "hardness classes" for metals can be connected with other shapes of tools and other qualities of tool steel, other depths of cut, and other thicknesses of feed, by reference to the various tables and formulæ given throughout this paper.

1138 In using this classification it will be noted that the best modern high speed $\frac{7}{8}$ inch tool, if cutting metal belonging to Class 1 would have a cutting speed of 316 feet per minute with a standard $\frac{3}{16}$ inch depth of cut and $\frac{3}{16}$ inch feed; and such a metal as this would be much softer than any steel which is cut in a machine shop.

1139 By referring to paragraphs 545 to 747, it will be seen that for what we call a hard steel forging of about the quality of a hard locomotive tire, a cutting speed of 45 feet corresponds to Class $21\frac{1}{4}$, while a soft steel having a cutting speed of 198 feet corresponds to Class $5\frac{3}{4}$.

1140 Having a clearly defined hardness classification of this sort for metals enables us to tie all of our experimental and practical work for years past together, even although tools of different chemical composition, and therefore of different cutting speeds, were used. This system of classification is also admirably suited for use on a slide rule.

THE EFFECT OF THE QUALITY OR HARDNESS OF STEEL FORGINGS UPON THE CUTTING SPEED

1141 There are three important elements which affect the hardness or the cutting properties of steel forgings:

a Their chemical composition.

b The thoroughness with which the metal is forged, that is, the amount that the cross-section of the ingot has been reduced in making the forging and the forging heat.

c The subsequent heat treatment which the forging receives, that is, whether it has been laid down to cool in the air, annealed, or oil hardened, and the exact temperatures of annealing and the rapidity of cooling.

1142 All of these three elements are so complicated that for men not engaged in the manufacture of steel there is but little use in attempting to consider them. It may be said, however, that for steel containing 0 .40 per cent of carbon or less, the percentage of carbon is a fairly reliable guide to the hardness or cutting speed.

BEST GUIDE TO HARDNESS AS IT AFFECTS CUTTING SPEEDS LIES IN THE PHYSICAL PROPERTIES OF STEEL AS INDICATED BY THE TENSILE STRENGTH AND PERCENTAGE OF STRETCH AND THE CONTRACTION OF AREA OF STANDARD TENSILE TEST BARS CUT FROM THE BODY OF THE FORGING

1143 The physical properties of steel constitute a fairly accurate guide to its cutting speed; and these properties are best indicated by the tensile strength and percentage of stretch and contraction of area obtained from standard tensile test bars cut from such a position in the body of the forging as to represent its average quality and then broken in a testing machine.

1144 It is of course impossible in most cases for any ordinary machine shop to cut test bars from the forgings which are actually used in the shop. It is, however, entirely possible and in many cases desirable to purchase forgings and castings with certain guaranteed tensile strength, stretch and contraction, and thus insure both the superior quality of the metal bought, and at the same time obtain metal practically uniform in its cutting speed. In our search for a guide to the cutting speed of metals, this has proven the only reliable index to the cutting speed.

1145 On Folder 23, Table 141, and also on Folder 12, Tables 81 and 83, we record a large number of steel forgings which were accurately standardized by us in the course of our experiments. Their chemical composition and physical properties will be found opposite the cutting speeds for our standard $\frac{7}{8}$ inch tool, with standard 20-minute cut, $\frac{3}{16}$ inch depth of cut and $\frac{1}{16}$ inch feed, the speeds in one column corresponding to tool No. 27 (Folder 21) and in the other column to tool No. 1 (Folder 20).

1146 We have purposely given a large number of forgings, many of them of chemical composition and physical properties closely resembling one another, in order to show that no absolute and accurate relation exists between the cutting speeds of forgings whose chemical, and even physical, properties very closely agree. A study of this table, however, will show that in general the cutting speeds grow slower as the percentage of carbon in the steel to be cut grows greater. In general, also, it will be noted that the cutting speed becomes slower as the tensile strength of the metal becomes higher, and that the cutting speed grows faster as the percentage of stretch increases.

1147 We have discussed at considerable length in paragraphs 506

to 579 (theory as to why pressure has no relation to cutting), a theory explaining why the cutting speed increases with an increase of stretch and diminishes with an increase of tensile strength. It may be proper to add that there are two reasons for a falling off in the percentage of stretch in steel forgings or castings; one of these being an increase in the hardness of the metal, and the other being an inferiority in the quality of the metal.

1148 Now a falling off in stretch due to increased hardness in metal will cause a slower cutting speed in the tool, while a falling off in the percentage of stretch due to an inferior quality of metal will not necessarily cause a slower cutting speed. For this reason the physical properties of steel are not an exact guide to the cutting speed unless the quality of the metal is clearly known. By *quality* we here mean whether it has been made of good material, well melted, forged, and has received proper subsequent heat treatment.

1149 We have developed the following empirical formula which is at least a partial guide to the cutting speed of steel of good quality when the physical properties of the forging are known as represented by a standard test bar 2 × ½ inch cut from the body of the forging and broken in a testing machine.

$$V = \frac{125\left(1-\frac{215}{(15+E)^2}\right)}{\sqrt{\frac{S}{10000}}-3-0.9}$$

In which V = Standard cutting speed;
S = Tensile strength in pounds per square inch;
E = Percentage of elongation of specimen 2″ x ½″.

1150 The cutting speed as represented by this formula will be found in the colmun in Folder 23, Table 141, opposite the actual speeds obtained from running the tools, and an inspection of the figures given in these two columns will indicate the degree of accuracy with which the formula represents the facts.

1151 It will be noted that in the very highest cutting speeds and also in the slower cutting speeds no values are given in the column for the formula. We omit these values because at both the high and low extreme limits, the formula does not correspond closely to the facts. We do not, therefore, feel satisfied with this formula, and shall endeavor to find a better substitute.

1152 It is well known that in the harder grades of steel, particularly those which are harder than hard tire steel, both the tensile

strength and the percentage of stretch are variable, that is, materially different results will be shown from test bars cut from the same forging. For this reason also the tensile strength and stretch, in our judgment, will never prove an accurate guide to the cutting speed of very hard forgings. However, it is the best guide at present known, and therefore has a certain value.

1153 We have tried experiments along several different lines in our endeavor to find some quick and reliable index to the hardness (*i. e.*, the qualities which affect the cutting speed) of forgings and castings, all, however without satisfactory, practical results. Among these we would mention:

a the ordinary abrasive tests in which metals of known hardness are used to scratch the metal to be examined;

b indenting the metal which is to be cut by pressing a punch or knife edge with a given pressure down into the face of the metal to be tested, and then measuring the extent of the indentation.

c The use of a special drilling machine, in which standard drills are used under definite pressure, and in which the distance drilled in a given number of revolutions is measured.

1155 The best apparatus of this type has been gotten up by Mr. William J. Keep, of Detroit, Mich. This is useful for certain castings, particularly when they are produced in the same foundry and from mixtures which are in a general way similar from day to day. It is applicable, however, to a comparatively small range of work.

1156 One of the greatest needs in the art of cutting metals is a more accurate standard by which to foretell the cutting speed of forgings and castings, and this should form a subject for future experiments.

EFFECT OF THE QUALITY OR HARDNESS OF THE CAST IRON UPON THE CUTTING SPEED

1157 It is much more difficult to predict the correct cutting speed for cast iron than for steel, and as yet no reliable method for doing this has come to our attention.

1158 Viewed from the standpoint of chemical analysis, the cutting speed becomes slower, the larger the amount of combined or cement carbon contained in the casting, and the cutting speed becomes less the smaller the amount of silicon contained in the casting. The amount of combined carbon, however, depends largely upon the rate or rapidity with which the cast iron has been cooled

after being poured into the mold; so that the mixture of the metal in the cupola does not constitute an accurate guide to the hardness of castings.

1159 It is needless to call attention to the fact that thin sections of cast iron which are cooled rapidly are harder and must be cut at slower cutting speeds than thick sections of metal made from the same heat and cast at the same time. Therefore, a study of the hardness of castings as it affects their cutting speeds must be made in each machine shop upon the particular castings actually used in order to obtain reliable results.

THE QUALITY OF RED HARDNESS IN TOOLS PLAYS A MUCH SMALLER PART IN CUTTING CAST IRON THAN IN CUTTING STEEL THEREFORE, WITH HIGH SPEED TOOLS THERE IS A MUCH LESS PERCENTAGE OF GAIN IN CUTTING CAST IRON THAN IN CUTTING STEEL

1160 It is a constant source of surprise that the high speed tools do not make the same proportionate gain in cutting cast iron as they do in cutting steel. Exact figures will be found in the table on Folder 20, where by comparing the cutting speeds of tools No. 85 (old fashioned carbon tempered tool) and No. 65 (old style Mushet self-hardening tool) with the best high speed tool No. 1, it will be noted that in cutting cast iron the best high speed tool cuts only about three and one-third times as fast as the old fashioned carbon tool, while when cutting both very hard and medium steel, the new high speed tool cuts between six and seven times as fast as the carbon tool.

1161 We have given in paragraph 523 a partial explanation of these facts. A further explanation of this curious phenomenon lies in the fact pointed out in paragraphs 864 to 866, that the most important property, namely, that which gives the great improvement in the high speed tools over the old fashioned tools, lies in the quality of red hardness which is possessed by these tools and which does not exist in the old tools.

1162 It will be remembered that red hardness is the quality which enables a tool to withstand that portion of the wear which is caused principally by the heat produced through the pressure of the chip on the tool.

1163 Now, in cutting almost all qualities of cast iron, the wear on the tool is due to two causes:

a the abrasive or grinding action of the carbon or gritty matter contained in the body of the iron itself; and

b the heat generated by the pressure of the chip upon the tool.

1164 In resisting the second of these causes for injury to the tools (*b*) the quality of red hardness tends greatly to increase the cutting speed. However, there is no doubt that the first of the two causes (*a*) plays much the more important part in injuring tools which are cutting cast iron, and in resisting this abrasive action the quality of red hardness is of but little use. For the same reason also, in cutting sand on the outside of castings or a mixture of sand and iron, the high speed tools are but little better than the old fashioned self-hardening tools.

CUTTING SPEED OF CASTINGS AS FOUND IN THE AVERAGE MACHINE SHOP

1165 As a broad general guide to the cutting speeds to be used for cast iron with the scale on the castings just as they come from the foundry, we would state that as the average of several machine shops in this country, it is our observation that medium cast iron may be said to belong to Class No. 18 to 19 in our scale of hardness, and that when cutting with a standard $\frac{7}{8}$ inch tool, of the quality of steel tool of No. 1, Folder 20, Table 138, with a standard 20-minute cut, a $\frac{3}{16}$ inch depth of cut and $\frac{1}{16}$ inch feed, they have a cutting speed of 60 feet per minute. On the whole, what may be called the hardest castings frequently met with in machine shops are not harder than Class No. 24, giving a standard cutting speed as mentioned above of 35 feet per minute. While softer castings quite frequently met with are as soft as class No. 11, and have a standard cutting speed of 120 feet per minute.

EFFECT OF SCALE ON CAST IRON CASTINGS UPON THE CUTTING SPEED

1166 As to the effect of the average scale met with in castings in the average shop, our experience indicates that with very soft castings the average scale met with calls for a cutting speed only about one-half as fast as the cutting speed of the same casting below the scale, and that as the castings grow harder and harder, the cutting speed of the scale approaches that of the cast iron below the scale, so that with the castings referred to just above as "hard" castings, the cutting speed of the scale and of the metal below the scale is about the same. On the medium castings referred to, the cutting speed of the scale may be said to be, in general, about three-fourths as fast as the cutting speed below the metal of the scale.

1167 In pars. 1163 and 1167 we refer to the effect of sand or a mixture of sand and iron upon the cutting speed of tools. In addition to this, however, we would state that when castings are made containing a mixture of sand and iron, far more work can be done by taking very coarse feeds, and we suggest as the standard remedy in machine shop practice, when these conditions are met with, the taking of a cut sufficiently deep to get well under the scale and then the use of as coarse a feed as practicable.

1168 It is obvious that in many cases, owing to the light sections of metal being cut or owing to lack of pulling power in the machine, it is impossible to take very coarse feeds or very deep cuts. It by no means follows that when these coarser feeds are taken, an exceedingly slow cutting speed must be used. In many cases the coarse feeds when cutting mixtures of sand and iron can be accompanied by fairly high cutting speeds.

LINE OR CURVE OF CUTTING EDGE

EFFECT OF LINE OR CURVE OF THE CUTTING EDGE ON THE CUTTING SPEED

1169 In paragraphs 278 to 315 we have pointed out the effect which the curve or outline of the cutting edge has upon the cutting speed, and we have endeavored to make it clear that the curve of the cutting edge of the tool affects the cutting speed chiefly because of the variation in the thickness of the chip or shaving which it produces. In general, the larger the radius of curvature of the cutting edge and the more nearly the general curve of the cutting edge lies parallel in a general way to the center line, or axis, of the work which is being cut, the thinner becomes the shaving and the higher the cutting speed.

TOOL WITH CUTTING EDGE HAVING A CURVED OUTLINE PRODUCES A CHIP VARYING IN THICKNESS AT ALL POINTS

1170 We have also, in these paragraphs, endeavored to make it clear:

(*a*) That a cutting edge, with a curved outline, invariably produces a shaving which varies in its thickness at all points

1171 In Folder 16, Figs. 112 and 111, and in Folder 17, Fig. 120, (enlarged views of our standard $\frac{1}{2}$ inch to $1\frac{1}{4}$ inch tools) are given (on a scale enlarged, in one case, sixteen times the full size of the tool, and in the other case eight times the size of the tool) views of the actual sections of the chip as removed by tools having different shaped cut-

ting edges. By referring particularly to Folder 17, Fig. 120 (enlarged view of ½ to 1¼ inch tool) in the case, for instance, of a cut ⅛ inch in depth, the large difference in the shaving which is produced in one case by our ½ inch standard tool, and in the other case by our 1¼ inch tool, will be clearly seen.

LARGE CURVE FOR CUTTING EDGE. THINNING DOWN THE SHAVING PRODUCES FASTER CUTTING SPEED

1172 By referring to our Practical Tables (Folder 24, Figs. 143 and 148) for cutting steel, using ⅛ inch depth of cut and $\frac{1}{16}$ inch feed, in the one case, with our standard 1¼ inch tool, and in the other case, with our standard ½ inch tool, the difference in the cutting speed produced by the thinning down of the shaving, owing to the change in the curve, will be observed. The thinner shaving accompanying the 1¼ inch tool in cutting medium steel, for instance, gives a cutting speed of 112 feet per minute as against a cutting speed of 81 feet for the thicker shaving of the ½ inch tool.

1173 It is obvious that some general law must exist for determining the relative cutting speed of tools having different curves for the outline of their cutting edges and that we should be able to determine this law by plotting on an enlarged scale the exact shape of the two sections of shavings which are being removed, as has been done in Folder 16, Fig. 112, and Folder 17, Fig. 120, and then comparing these shapes with their corresponding cutting speeds. We have once or twice started on this line of investigation, but have never had the time, or as yet sufficient data, to enable us to determine accurately this law, and this would seem to form an important subject for future investigation.

THE CUTTING SPEEDS OF OUR STANDARD TOOLS OF DIFFERENT SIZES COMPARED WHEN USING THE SAME DEPTH OF CUT AND FEED

1174 A comparison of the cutting speeds given in the Practical Tables (Folder 24), with the cross-sections of the chips shown in Folder 17, Fig. 120, will indicate the effect on the cutting speed of the various sections of shavings produced by different depths of cut and thicknesses of feed when using our several standard shapes of tools, varying from ½ inch up to 1¼ inch. In addition to obtaining this information we have at various times made experiments to determine the relative cutting speeds of shop tools which are in ordinary use and which differ very radically in the curve of their cutting edges. The time when it is necessary to publish this paper is so close

at hand that the writer is unable to give the full data connected with these various experiments. As a matter of interest, however, we record the following general results of this work.

EXPERIMENTS UPON THE CUTTING SPEEDS OF PARTING TOOLS AND THREAD TOOLS

1175 Two sets of these experiments are of especial interest. One set was made during the year 1888 in the works of the Midvale Steel Co. upon a large steel locomotive tire, and the other in 1893 at the works of the Link-Belt Engineering Co., of Philadelphia, upon the very thick rim of a cast iron fly wheel. It so happened that the men who were experimenting upon the cast iron fly wheel did not know of the experiments previously made upon the steel tire, and as the results of these two sets of experiments agree within from 3 per cent to 4 per cent, the probability of their being reliable is all the greater. These experiments were undertaken to determine accurately the relative cutting speeds for a parting tool and a thread tool when compared with our standard $\frac{7}{8}$ inch round nosed tool, and also with a tool having a straight line cutting edge, cutting a shaving of uniform thickness throughout.

1176 By a "parting tool" we mean a narrow, square nosed tool which is fed directly "end on" into the work for the purpose of cutting it or slicing it into two pieces. The two corners of the parting tools experimented with were rounded to the extent of about $\frac{1}{64}$ of an inch.

1177 By a "thread tool" we mean the ordinary tool for cutting the United States Standard V Threads, having a 60 degree included angle. The extreme point of this thread tool was also squared off to the extent of about $\frac{1}{64}$ of an inch.

1178 In cutting the steel tire, two different thicknesses of feed were used, namely, 0.0156 inch and 0.203 inch; in cutting cast iron also, two different feeds were used, namely, 0.0166 inch and 0.029 inch.

1179 In each case the standard cutting speed was found, for the parting tool, when it was only so badly injured that it could be economically reground by grinding away the clearance flank of the tool only. In each case the ratio of the cutting speed of the parting tool with a given feed to that of a tool with a straight line cutting edge having $\frac{1}{2}$ inch in length of the cutting edge under cut, and in which neither of the extreme corners of the tool were cutting metal, was as 0.66 : 1 when both tools were taking the same thickness of feed, that is, cut-

ting chips of exactly the same thickness. The ratio of 0.66 : 1 was found to hold true when successively a thickness of chip of 0.0166 inch and of 0.029 inch were used with both tools, and also when different "durations of cut" were used with both shapes of tool. In one case a duration of cut of 20 minutes was experimented with for both tools and in the other case a duration of 60 minutes was used.

1180 The ratio of a thread tool to a tool with a straight line cutting edge under the same conditions, that is, when both were fed with the same feed, "end on," straight into the work, was as 0.45 : 1.

PRACTICAL RULE FOR FINDING PROPER CUTTING SPEED FOR A PARTING TOOL WHEN HIGH SPEED STEEL OF QUALITY OF TOOL NO. 1, FOLDER 20, IS USED

1181 The practical problem, however, for the man who is running a machine shop is to find quickly, when he has a given quality of metal, at just what speed he must run his parting tool or his thread tool to do the work with the greatest economy; and we would suggest the following as a practical rule for obtaining the desired cutting speed.

1182 Referring to our practical tables for cutting steel and cast iron on Folder 24. Find first the feed, *i. e.*, the thickness of the chip which is to be cut by the parting tool; then look in the practical table for cutting steel or cast iron as the case may be (Folder 24), for our standard $\frac{7}{8}$ inch tool under $\frac{3}{16}$ inch depth of cut and with the thickness of the feed which corresponds most nearly to the given thickness of the chip which is to be taken by the parting tool; read off the cutting speed from this table, and divide it by 2.7, and this will give the proper cutting speed for the parting tool.

1183 In other words, if we take the practical economical cutting speed of our $\frac{7}{8}$ inch standard round nosed tool when using $\frac{3}{16}$ inch depth of cut and a feed which is the same as the thickness of chip to be cut by the parting tool, the speed of our standard tool under these conditions will be 2 .7 times as fast as the proper speed for the parting tool.

PRACTICAL RULE FOR FINDING PROPER CUTTING SPEED FOR A THREAD TOOL WHEN HIGH SPEED STEEL OF THE QUALITY OF TOOL NO. 1, FOLDER 20, IS USED

1184 If in the same way we first determine the thickness of the chip over the point or extreme nose of the thread tool, *i. e.*, if we determine the exact advance of the thread tool toward the center line

of the work each time a cut is taken, and call this advance the thickness of the chip; and if we then proceed as described just above in the case of the parting tool, it will be necessary to divide the speed obtained for our standard round nosed tool by 4. Or, in other words, if we take the practical economical cutting speed of our $\frac{7}{8}$ inch standard round nosed tool when using a $\frac{3}{16}$ inch depth of cut and a feed which is the same as the advance of the thread tool toward the center line of the forging which is made after each cut taken by the thread tool, the speed of our standard tool under these conditions will be four times as fast as the speed of the thread tool.

1185 More or less difficulty will be found in applying both of these rules, owing to the fact that in our practical tables (Folder 24) we have not given a large enough variety in the fine feeds. If time permitted we should give tables for the proper cutting speeds of thread tools and parting tools.

CUTTING SPEED OF BROAD NOSED TOOLS WITH STRAIGHT LINE CUTTING EDGE COMPARED WITH STANDARD $\frac{7}{8}$ INCH ROUND NOSED TOOLS

1186 To show the relation in cutting speed existing between our standard $\frac{7}{8}$ inch round nose tool and a tool having a straight line cutting edge, cutting a shaving exactly one inch long, as shown in Folder 7, Fig. 35: If these two tools are set so as to take a depth of cut exactly $\frac{3}{16}$ inch, with a feed of 0.08 inch, then

$$\text{the cutting speed of our standard round nosed tool} : \text{the cutting speed of the straight edged tool} :: 17 : 24$$

In other words, if we know the cutting speed of our $\frac{7}{8}$ inch standard tool, and wish to find the corresponding cutting speed for a straight edge tool having one inch of cutting edge under cut, multiply the cutting speed of our standard tool by 1.4.

1187 In paragraphs 312 to 314 we have referred to standard shapes for tools with broad cutting edges which we adopted and practically used for several years with excellent results. These broad nosed tools are shown in Folder 7, Figs. 32, 33 and 34. When taking the same depth of cut and the same feed

$$\text{the cutting speed of our standard round nosed tool} : \text{the cutting speed of the straight edged tool} :: 17 : 22$$

Or, if we know the cutting speed of our standard $\frac{7}{8}$ inch tool, and wish to find the corresponding cutting speed of a broad nosed tool, multiply the cutting speed of the standard tool by 1.3. The relation between

the cutting speeds of these types of tools was determined by us years ago with tools made of carbon tempered steel. They should again be accurately established through experiments with the best high speed tools.

SLIDE RULES

1188 Under the head of slide rules we refer to the practical solution of the mathematical problem which includes the laws as to the effect of the Twelve Variables referred to in paragraph 135 upon the three great questions:

WHAT DEPTH OF CUT SHALL BE USED?

WHAT FEED SHALL BE USED?

WHAT CUTTING SPEED SHALL BE USED?

1189 The practical and successful use of these laws as embodied in slide rules has been referred to by us in paragraphs 7 to 16, and in paragraphs 51 to 53 we have briefly described some of our efforts at solving this problem and the difficulties which we have met with. It may be of interest, however, to go somewhat more into detail upon this subject with a view to indicating in general the steps taken by us in its solution.

1190 Almost as soon as we had succeeded in developing formulæ which represented the results of our experiments, we realized the seriousness and difficulty of the problem before us in endeavoring to make practical and everyday use of these results. The first mathematical solution of the problem was made by Mr. G. M. Sinclair, who devoted, as the writer remembers, a year or more of consecutive work to this end with the help and advice of the writer.

1191 This solution was accomplished by means of overlying curves plotted on ordinary cross-section paper, with which we were able to work out laboriously and exceedingly slowly for each particular lathe or planer, a set of tables which could be used for most of the conditions met with in ordinary work. This method was, however, so exceedingly slow and laborious as to make it far from generally useful.

1192 After Mr. Sinclair left the problem, Mr. H. L. Gantt devoted a year or more of his time almost exclusively to its solution, and it was during this period that we substituted curves laid out on logarithmic paper for the direct curves laid out on ordinary cross-section paper. As a result of this work, we obtained a logarithmic sheet upon which both diagrams and figures were used to represent the laws, and by means of an elaborate cross slide, upon which further elements of the laws were entered, we were able to make a more rapid and much

more direct solution of the problem. This was done, however, by the method of trial and error, but by means of this crude sliding table we were able to make quite rapid approximations to the proper working conditions.

1193 It was not until after we began our experiments at the works of the Bethlehem Steel Company that we finally gave up the hope of obtaining a mathematical solution of this problem through the aid of some of the more noted mathematicians, as referred to in paragraphs 51 to 53. Mr. Gantt and the writer again attacked the mathematical side of the problem at Bethlehem, and substituted an especially made slide rule accompanied by diagrams, by means of which a still more rapid solution of the problem was obtained. When in this state Mr. Carl G. Barth joined our work, and together Mr. Barth, Mr. Gantt and the writer developed the final slide rule illustrated in Folder 11, Fig. 79, by means of which the problem is directly and very quickly solved. This slide rule has since been patented jointly by Messrs. Barth, Gantt and the writer. As before stated, however, Mr. Barth is a better mathematician than either Mr. Gantt or the writer, and it is very largely to his long continued work both on the slide rules and in revising the expressions for the laws that the present solution of the problem is due.

1194 We had intended describing in detail the best method of procedure for incorporating the various laws given throughout the paper upon our latest type of slide rule, as indicated, in Folder 11, Fig. 79. The greater part of this paper, however, is already in print, and there remain but a few hours before the last section of the work must be in the hands of the printer. It is therefore with regret that this portion of the paper must be omitted. No mathematician, however, will have much difficulty in finding a comparatively easy method of incorporating those laws upon a slide rule.

1195 Attention is again called to the fact that all the mathematical formulæ representing the laws are suited for use on the slide rule. We have been limited to formulæ capable of logarithmic expression, and it is indeed fortunate that it has proved possible to represent fairly accurately with this single type of formula all of the laws referred to.

1196 In Folder 11, Fig. 78, is illustrated a circular slide rule made by Mr. Barth, which is used in connection with the lathe slide rule, Fig. 79, for quickly figuring the time required to do the work. Both of these slide rules are described by Mr. Barth in his paper, entitled "Slide Rules for the Machine Shop as a Part of the Taylor System of Management," published in Volume 25 of the Transactions.

1197 In paragraphs 113 to 119 the writer has indicated some of the difficulties attending the practical everyday use of these slide rules in machine shops, and has also stated the fact that he has no very great hope of their rapid introduction into practical use. He would add, however, that he looks upon task management as a matter of such great moment, both to the workmen in raising their wages and rendering strikes and labor troubles unnecessary and to the manufacturers in increasing and cheapening their output, that although he has personally retired from the active introduction of this system of management professionally, he is still devoting his time to furthering the introduction of this system, and expects to make this the main object of his remaining life's work. He wishes to state, therefore, that he will be glad at all times to assist through advice any company desiring to work along these lines.

ADDITIONAL EXPERIMENTS AND INVESTIGATIONS

1198 A lack of time prevents the writer from summarizing under one heading the various experiments and investigations which should be undertaken in the future to acquire more knowledge in this art. We have, however, from time to time throughout the paper suggested the great need for further work, and the writer expects in the future to prepare a short paper for the Society indicating what he believes to be the more important lines for investigation.

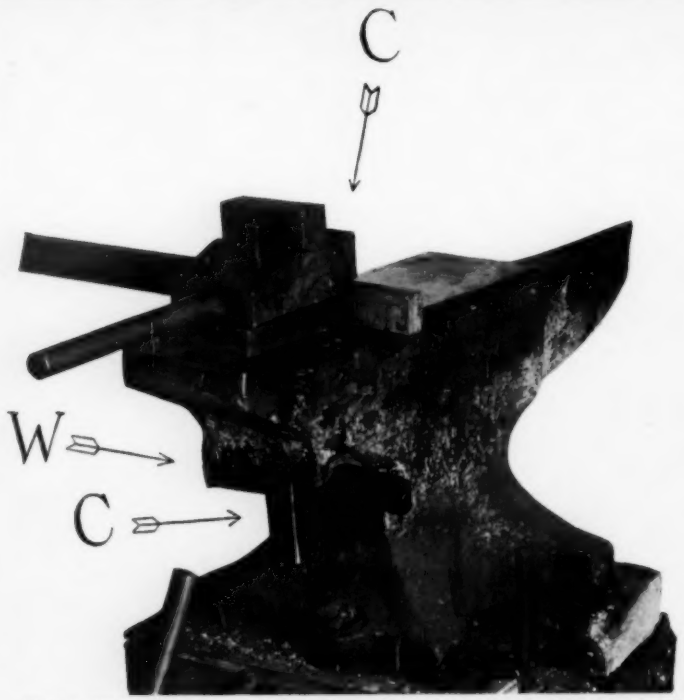


FIG. 1 TOOL CUT OFF FROM BAR AND CLAMPED ON SMITH'S ANVIL READY TO BEND DOWN (OR, AS IT IS TERMED, "TURNED UP")

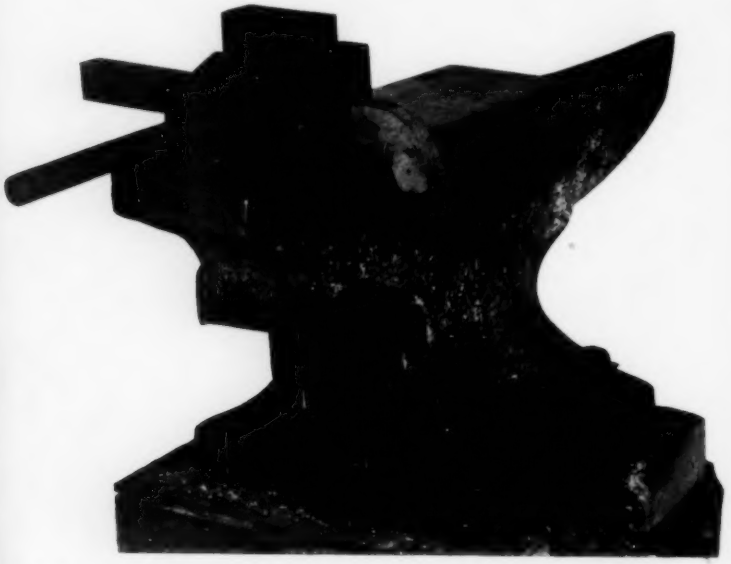


FIG. 2 TOOL BENT DOWN ACROSS EDGE OF THE ANVIL ("TURNED UP")

FIG. 3. HEEL OF TOOL BEING DRAWN DOWN UNDER STEAM HAMMER TO GIVE SUPPORT TO THE NOSE ALMOST DIRECTLY BENEATH THE CUTTING EDGE

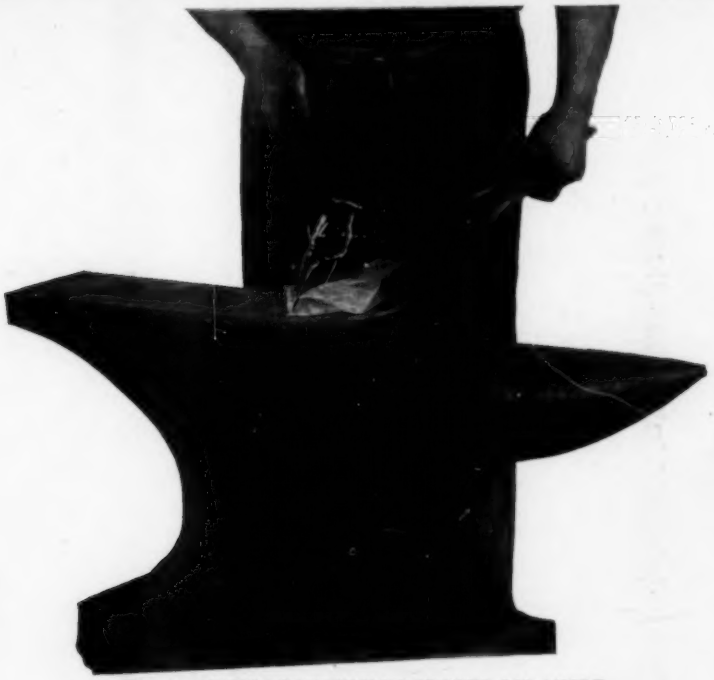


FIG. 4 CUTTING ROUGHLY TO PROPER LIP ANGLE

FIG. 5. CUTTING FRONT CORNERS OFF OF THE NOSE SO AS TO APPROXIMATE TO THE PROPER CURVE

FIG. 6 TRYING TOOL AGAINST CONE GAGE TO TEST PROPER ANGLE FOR NOSE

HOTOGRAPHS ILLUSTRATING BEST METHOD OF FORGING OUR STANDARD ROUND NOSE ROUGHING TOOLS BY A BLACKSMITH

For photographs of the tools at various stages in process of forging, see Folder 2, Figs. 7 to 13.

For detail drawing, giving dimensions of a sample tool, see Folder 6, Fig. 2 .

For the exact curves of the cutting edges, see Folder 5, Figs. 21 to 24, incl. (See paragraphs 325 to 333)

For photographs of this type of tool, two-thirds ground away, see Folder 3, Fig. 17c.

For forging directions, see paragraphs 391 and 469.

For outlines of standard Round Nose Tools from $\frac{1}{2}'' \times \frac{3}{8}''$ to $1\frac{1}{4}'' \times 1\frac{1}{8}''$, see Folder 5, Figs. 23 and 25a to 25e incl. (See paragraphs 325 to 333)

For limit gage for dressing these tools, see Folder 6, Fig. 29.

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

Fig. 7 Nose turned up on the anvil.
Fig. 8 Heel drawn down to give support close under cutting edge.
Fig. 9 Tool cut roughly to proper lip angle.
Fig. 10 Front corners cut off so as to approximate to proper curve.
Fig. 11 Diagonal view looking partly down upon the tool after grinding.
Fig. 12 End view of ground tool showing nose properly set over to one side.
Fig. 13 Tool about half used up.

PHOTOGRAPHS OF OUR STANDARD ROUND NOSE TOOL IN VARIOUS STAGES DURING THE OPERATION OF FORGING

For photograph of this type of tool, two-thirds ground away, see Folder 3, Fig. 17c.

For forging directions, see paragraphs 391 and 469.

For outlines of Standard Round Nose Tools from $\frac{1}{2}'' \times \frac{3}{4}''$ to $1\frac{1}{4}'' \times 1\frac{7}{8}''$, see Folder 5, Figs. 23 and 25a to 25e incl. (See paragraphs 325 to 333)

For limit gage for dressing these tools, see Folder 6, Fig. 29.

For photographs of best method of forging this tool by blacksmith see Folder 1,

For detail drawing, giving dimensions of a sample tool, see Folder 6, Fig. 28.

For the exact curves of the cutting edges, see Folder 5, Figs. 21 to 24 incl. (See paragraphs 325 to 333)

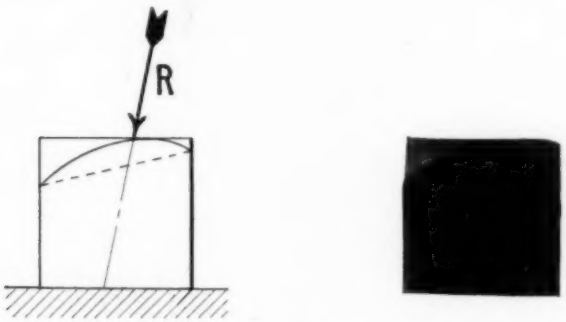


FIG. 14 ENGLISH AND OLD AMERICAN STANDARD SQUARE BODY TOOL

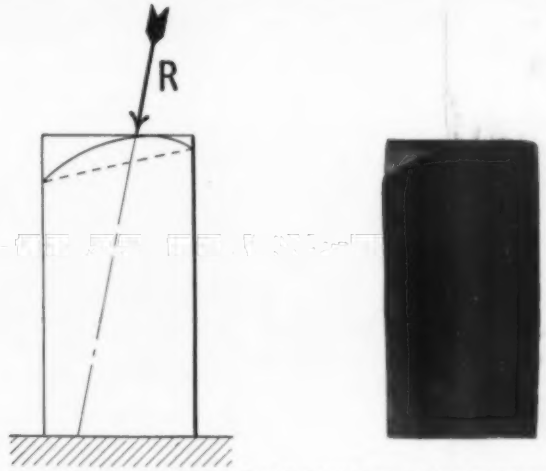


FIG. 15 RECENT AMERICAN STANDARD BODY FOR TOOL 1 WIDE BY 2 HIGH

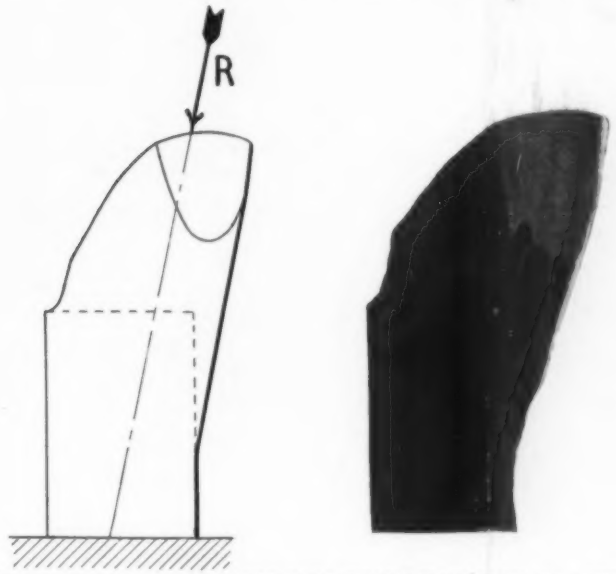


FIG. 16 STANDARD BODY FOR TOOL RECOMMENDED BY US, 1 WIDE BY 1½ HIGH

FIGS. 14, 15 and 16 WHY THE NOSES OF OUR STANDARD TOOLS ARE BENT TO ONE SIDE

Showing that with our standard tool, which has its nose bent over to one side, the resultant line of pressure R of the shaving on the cutting edge comes close to the center line of the base of the tool while with Recent American standard the resultant line of pressure R comes to one side of the center line of the base.

See paragraph 422 to 425. For drawings of our standard tools, see Folder 5, Figs. 23 and 25a to 25e incl.

FIG. 17a STEEL MOUNTED ON LIP SURFACE

Small particles of the chips scraped from the forging and pressed or welded into a compact pile upon the lip surface of the tool. (See paragraphs 170 and 174)

FIG. 17b RUINED

This tool was run at such high speed as to be ruined while cutting, marked "Ruined" on the notes and records of our experiment. (See paragraph 205)

FIG. 17c FAIR

Tool marked "Fair" on the notes and records of our experiments. This tool had been run at slightly too high cutting speed for standard time and showed slight signs of ruining when removed from lathe. (See paragraph 205)

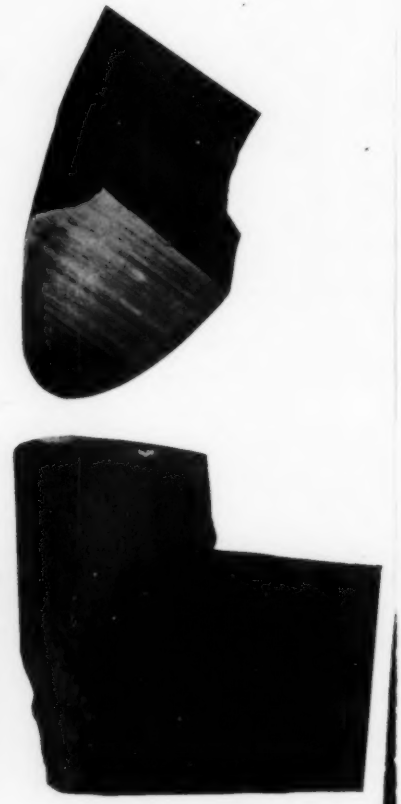


FIG. 17d GOOD

Tool marked "Good" on the notes and records of our experiments. This tool had run at maximum standard speed in one of our experiments and was still cutting right when removed from the lathe. (See paragraph 205)

PHOTOGRAPHS SHOWING THE TYPICAL WEAR ON MODERN HIGH SPEED TOOLS WHEN RUN AT CLOSE TO THEIR RUNNING SPEEDS. DEPTH OF CUT 3-16″, FEED 1-16″ CUTTING HARD STEEL

Figs. 17a to 17e show full sized photographs taken from tools made of steel No. 1, Folder 20, Fig. 138, namely, the best modern high speed tool. The depth of cut in all cases was $\frac{3}{16}$″ and the feed $\frac{1}{16}$″. All of these tools had been run at close to their standard speeds but Fig. 17c and Fig. 17b had been run too fast and were respectively in "Fair" and "Ruined" condition while Fig. 17a, Fig. 17d and Fig. 17e were all in good condition, although rapidly approaching the ruining point. Fig. 17e illustrates the fact that the pressure of the chip is greater back from the cutting edge than at the cutting edge. The line of the cutting edge being still in good condition while a deep groove or gutter is worn in the lip surface from the heat and pressure of the chip. See paragraph 170. The chip which wore this groove was red hot at its extremities. Note also that this groove is more than $\frac{3}{16}$″ back from the cutting edge although a feed of only $\frac{1}{16}$″ was used, which illustrates the fact that the chip must be in process of being sheared or broken into sections at three places at the same time. (See Folder 8, Fig. 42, and paragraphs 153 to 170)

In Fig. 17a the pile of small particles of chips or dust scraped by the cutting edge off of the forging after the chip has been torn away from the forging is shown mounted up in a small compacted mound as described in paragraphs 170 and 174. These dust particles sometimes pile up $\frac{1}{8}$″ to $\frac{3}{16}$″ high, showing that the chip is torn away from the forging as described in paragraphs 170 to 174.

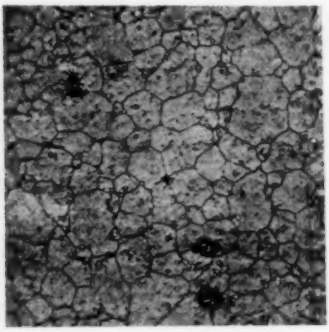
FIG. 17e TOOL GUTTERED

Cutting edge still good but deep groove worn or guttered in the lip surface by the pressure of the chip.

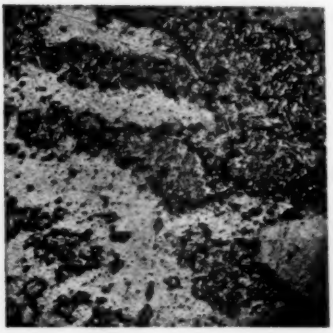
FIG. 18 PHOTOGRAPH ILLUSTRATING THE FACT THAT "RED HARDNESS," THE DISTINCTIVE PROPERTY OF HIGH SPEED TOOLS, DIFFERS MATERIALLY FROM THE PROPERTY OF HARDNESS

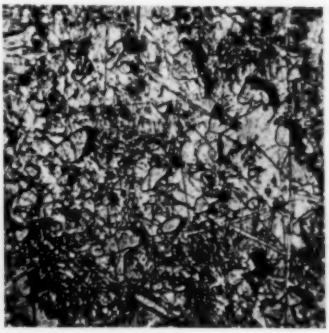
This tool was run at high speed cutting a steel forging and the nicks close to the portion of the cutting edge which did the work and filed in it afterward with an ordinary file show the tool to be soft in spite of its possessing a high degree of RED HARDNESS.

(See paragraphs— and—)

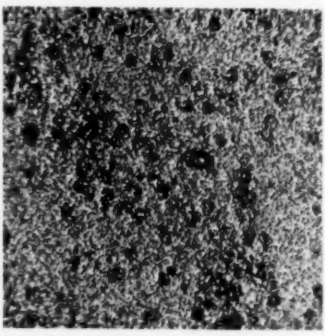


No. 19a After thorough hardening heated to 2192° Fahr.

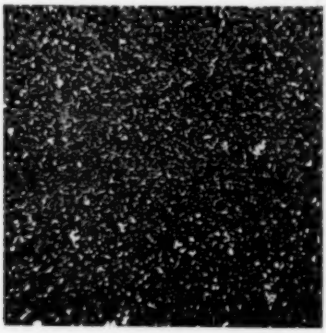




No. 19b and 19c After tempering or softening has begun by heating to 550° C., 1022° Fahr.



No. 19d After the tempering or softening has proceeded so far as to entirely change the original structure as shown in No. 19a heated to 600° C., 1112° Fahr.



No. 19e After tempering or softening is completed, heated to 700° C., 1292° Fahr.

FIGS. 19a, 19b, 19c, 19d and 19e **Characteristic Structures of Chromium-Tungsten Steels** heated to 1200° C., 2192° Fahr., and cooled as they would be to make a good, high speed tool.

Steels treated, specimens etched and photographs made by Prof. H. C. H. Carpenter, of Manchester, England.

These photographs illustrate the difference between "Hardness" and "Red Hardness." They show that high speed tools begin to soften at 1022° Fahr., while diminution in "Red Hardness" does not begin until after 1200° Fahr. has been passed, and the best high speed tools are made by reheating to 1150° Fahr.

See paragraph 1117, description of Professor Carpenter's work.

See paragraphs 979 to 1001, description of high temperatures for making a high speed tool.

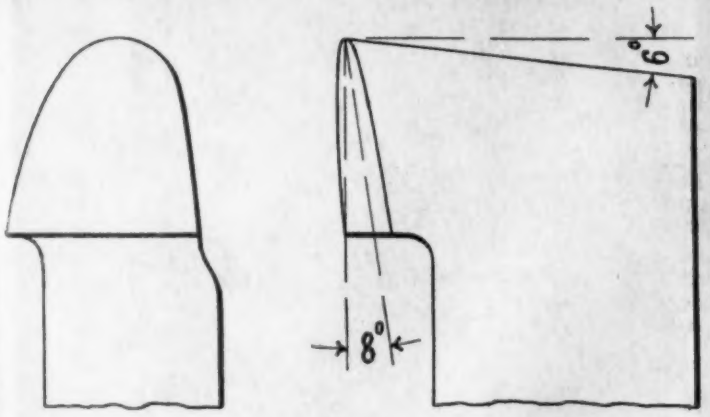


FIG. 20a

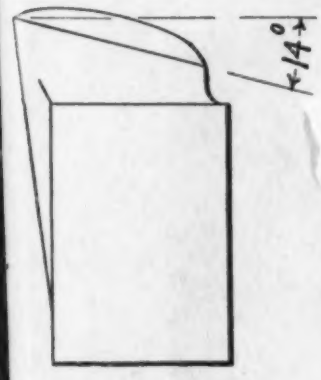
DRAWING SHOWING CLEARANCE ANGLE, BACK SLOPE AND SIDE SLOPE

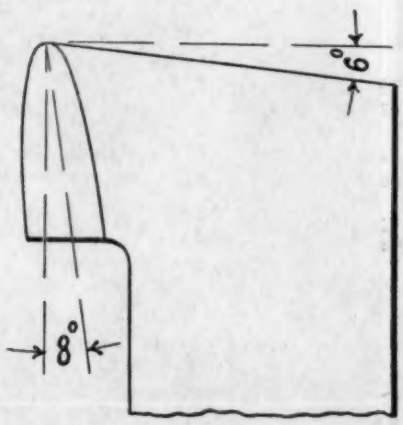
in our standard tools for cutting cast iron and hard steel.

Tool about two-thirds used up.

For definitions, see Folder 6, Fig. 30.

For new standard tools, see Folder 5, Figs. 23 and 25a to 25e.





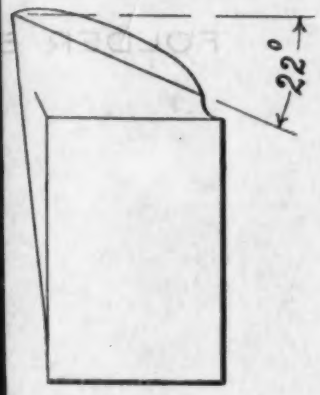


FIG. 20b

DRAWING SHOWING CLEARANCE ANGLE, BACK SLOPE AND SIDE SLOPE

in our standard tools for cutting medium and soft steel. Tool about two-thirds used up.

For definitions, see Folder 6, Fig. 30.

For new standard tools, see Folder 5, Figs. 23 and 25a to 25e incl.

FIGS. 25a to 25e OUTLINES OF STANDARD ROUND NOSE ROUGHING TOOLS from $\frac{1}{4}'' \times \frac{1}{4}''$ to $1\frac{1}{4}'' \times 1\frac{1}{4}$. (See paragraphs 325 to 333)

The broken lines show shape of tool as forged.

The solid lines show shape of tool as ground, for cutting hard steel and cast iron. These tools are ground to the following angles: Clearance angle 6°, back slope 8°, side slope 14°. (See paragraph 342)

For cutting medium steel and soft steel, these tools are ground to the following angles: Clearance angle 6°, back slope 8°, side slope 22°. (See paragraph 343)

For detail drawing, giving dimensions of a sample tool, see Folder 6, Fig. 28.

For the exact curves of the cutting edges see Folder 5, Figs. 21, and 22. (See paragraphs 325 to 333)

For forging directions, see paragraphs 391 and 469

For photographs of this type of tool, two-thirds ground away, see Folder 3, Fig. 17c.

For photographs of best method of forging these tools by blacksmith, see Folder 1, Figs. 1 to 5.

For photographs of these tools at various stages in process of forging, see Folder 2, Figs. 7 to 12.

For limit gage for dressing these tools, see Folder 6, Fig. 29.

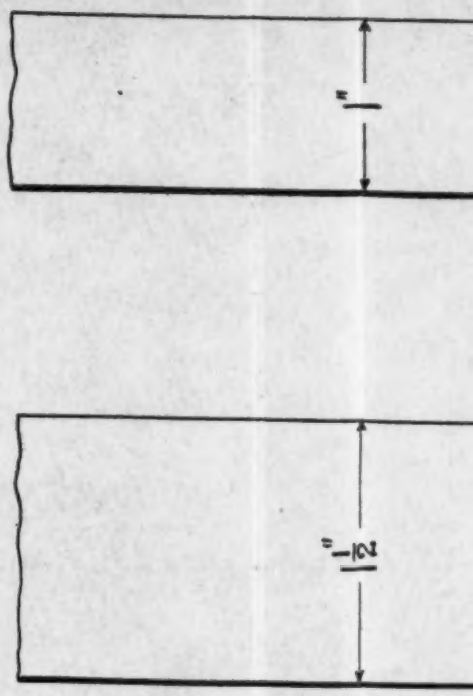
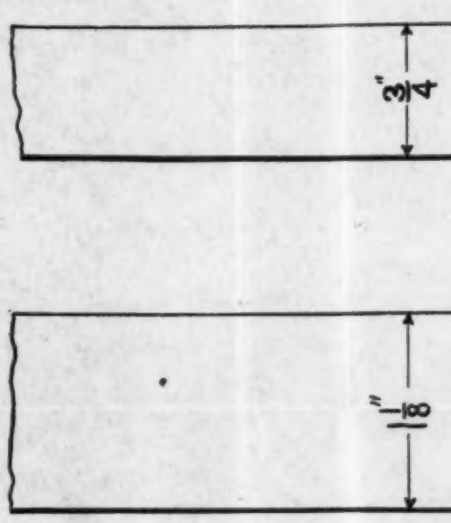


FIG. 25a



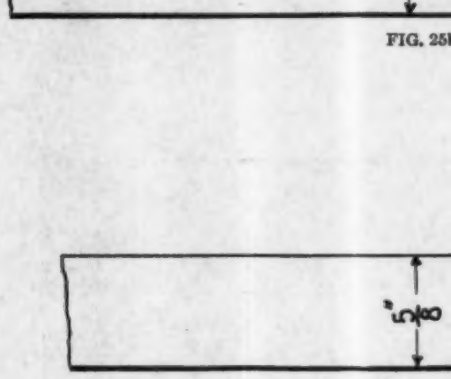


FIG. 25

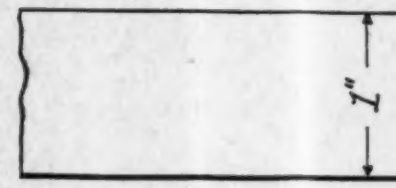


FIG. 25c

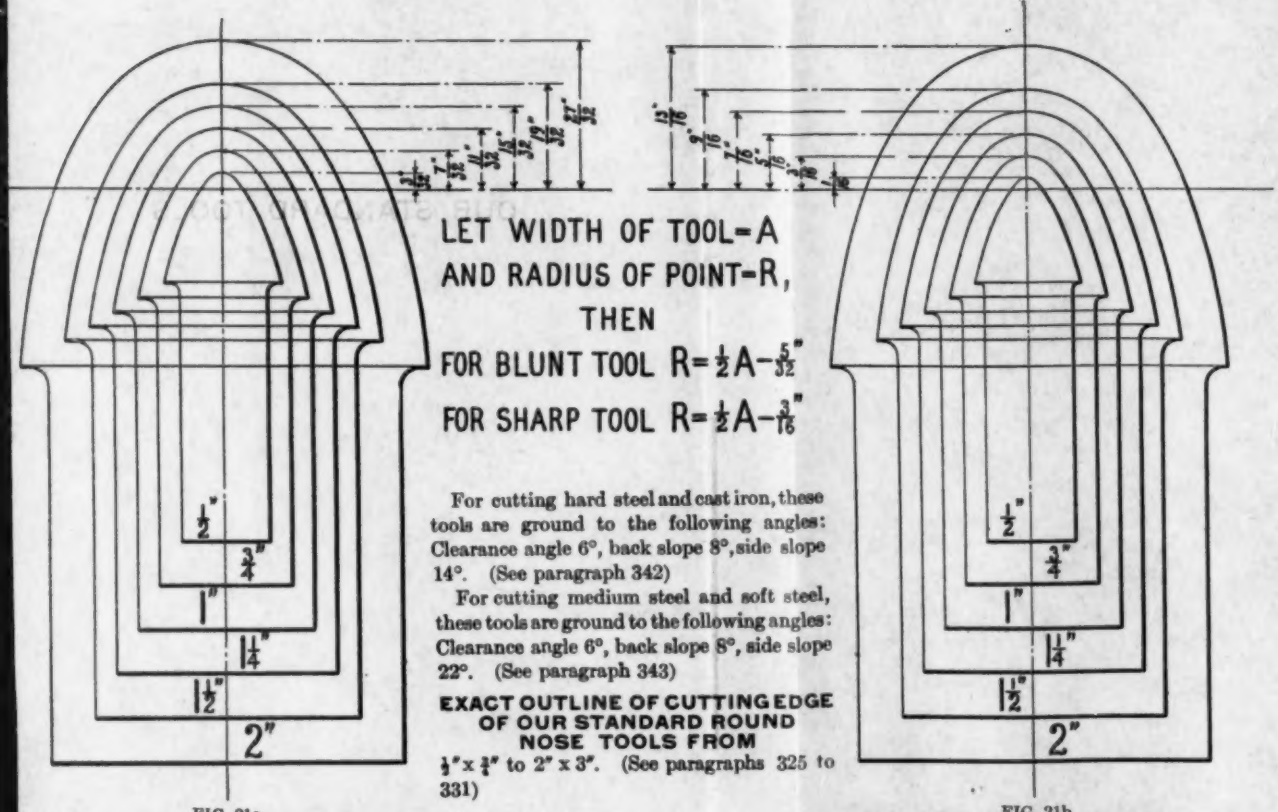


FIG. 21a

BLUNT TOOL FOR CUTTING HARD STEEL AND CAST IRON

FIG. 21b

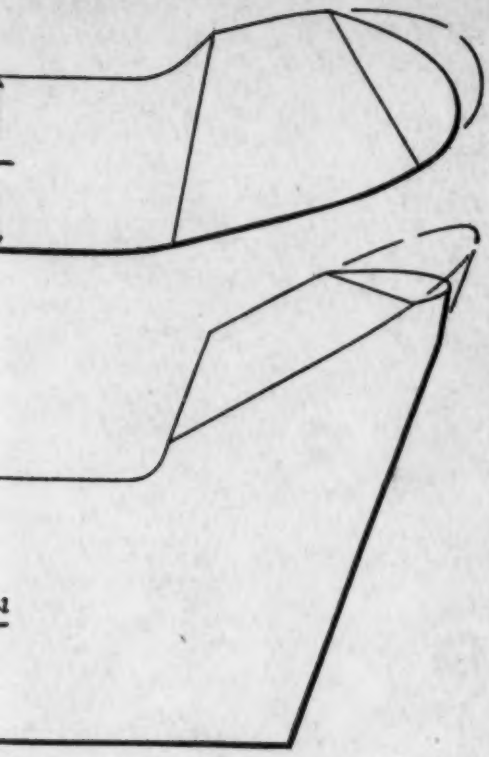
SHARP TOOL FOR CUTTING MEDIUM AND SOFT STEEL

For cutting hard steel and cast iron, these tools are ground to the following angles: Clearance angle 6°, back slope 8°, side slope 14°. (See paragraph 342)

For cutting medium steel and soft steel, these tools are ground to the following angles: Clearance angle 6°, back slope 8°, side slope 22°. (See paragraph 343)

EXACT OUTLINE OF CUTTING EDGE OF OUR STANDARD ROUND NOSE TOOLS FROM

$\frac{1}{2}'' \times \frac{1}{4}''$ to $2'' \times 3''$. (See paragraphs 325 to 331)



. 25a

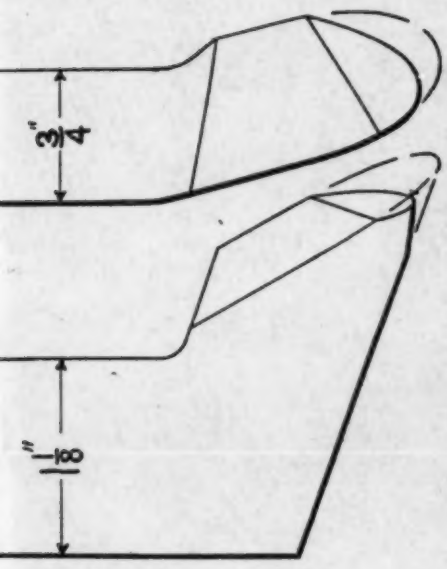


FIG. 25b

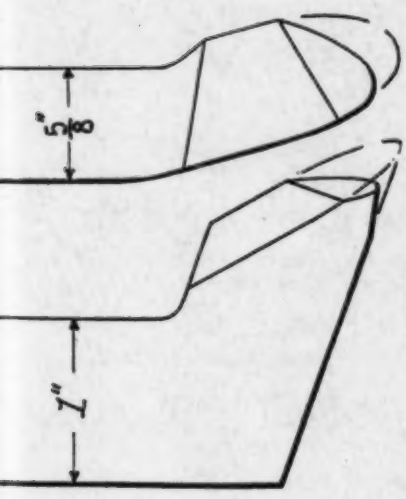


FIG. 25c

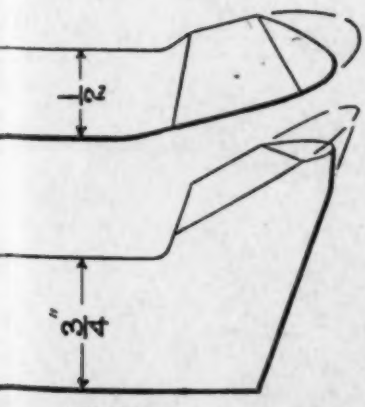


FIG. 25d

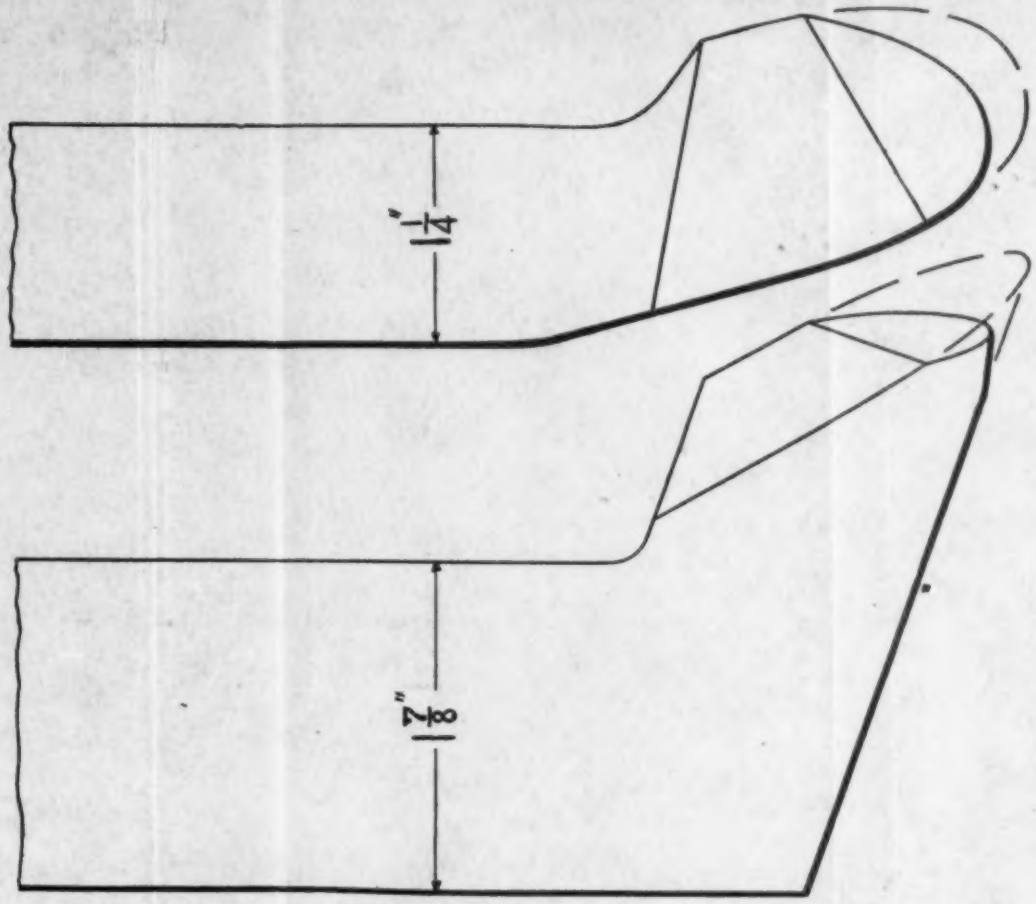


FIG. 25e

FIG. 22

STANDARD TOOL FOR WIDE FEEDS

Outline of cutting edge of tool for taking shallow depths of cut and wide feeds in cutting cast iron. (See paragraph 332)

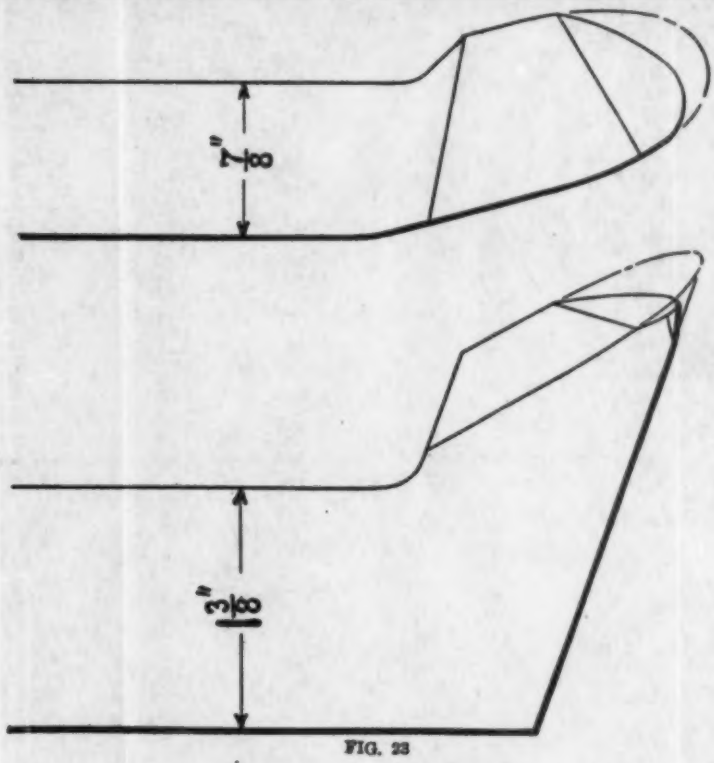
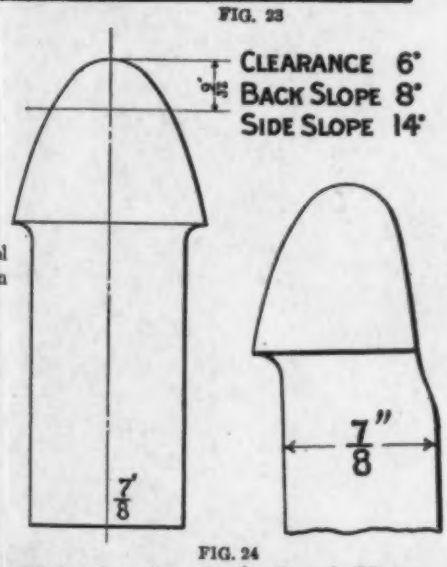


FIG. 23

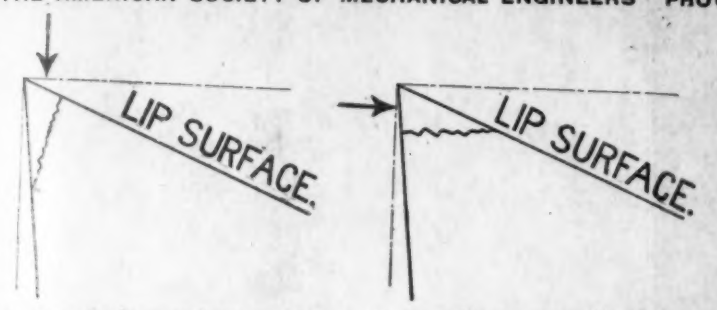


Shape of our standard $\frac{7}{8}$" tool corresponding to those given in Fig. 21a.

This is the shape of our $\frac{7}{8}$" round nosed standard tool two-thirds ground away. (See paragraph 325)

FIG. 24

Figs. 23 and 24 This is the standard $\frac{7}{8}$" Tool with which most of our experiments have been made



A From the downward pressure of the chip

B From the pressure on the clearance flank due to feeding the tool

FIG. 31

THE TWO WAYS IN WHICH CUTTING TOOLS SPALL OFF or crumble away at the cutting edge (See paragraphs 352 to 355)

TABLE 27 RULE FOR LENGTH OF ROUGHING TOOLS ADOPTED BY US
(See paragraph 430)

SIZE OF SHANK OF TOOL IN INCHES	LENGTH OF TOOL IN INCHES
½ x ¾	11
⅝ x 1	12¾
¾ x 1¼	14½
⅞ x 1⅜	16¼
1 x 1½	18
1¼ x 1⅞	21½
1½ x 2¼	25
1¾ x 2⅝	28½
2 x 3	32

Let Width of Shank of Tool = A
and Length of Tool = L
then L = 14A + 4"

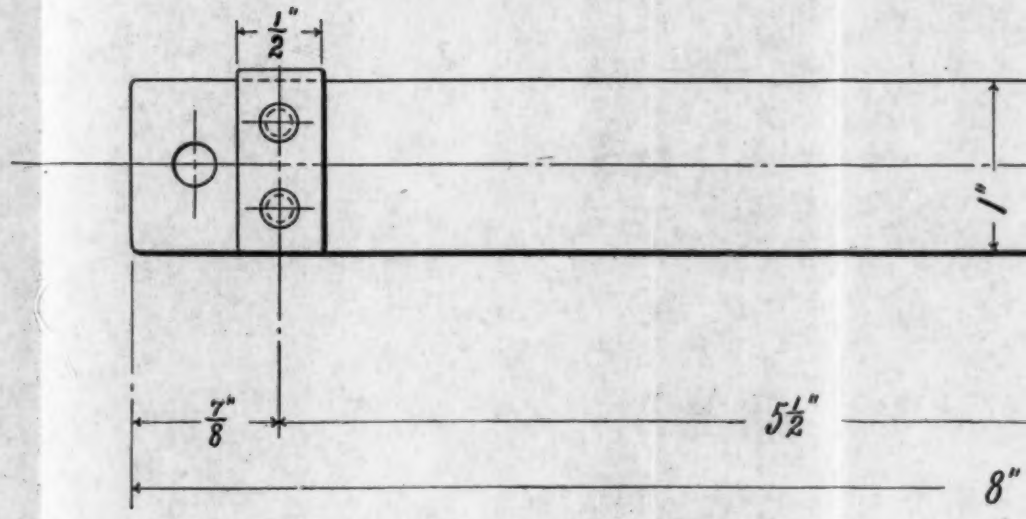


FIG. 29

LIMIT GAGE for forging the 1" Round Nose Roughing Tool, shown on Folder 5, Fig. 23 and 25a (See paragraph 471)

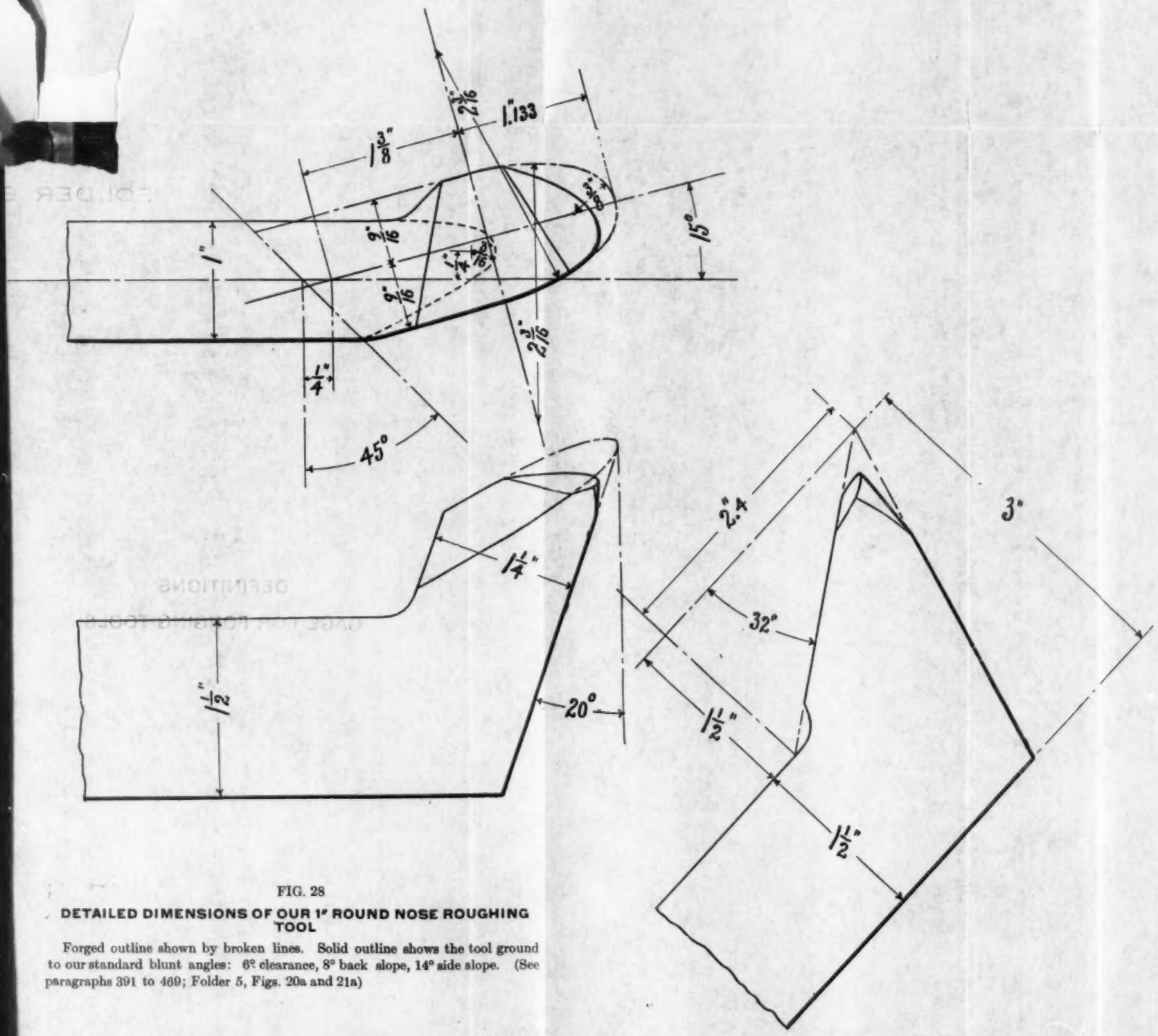


FIG. 28

DETAILED DIMENSIONS OF OUR 1" ROUND NOSE ROUGHING TOOL

Forged outline shown by broken lines. Solid outline shows the tool ground to our standard blunt angles: 6° clearance, 8° back slope, 14° side slope. (See paragraphs 391 to 469; Folder 5, Figs. 20a and 21a)

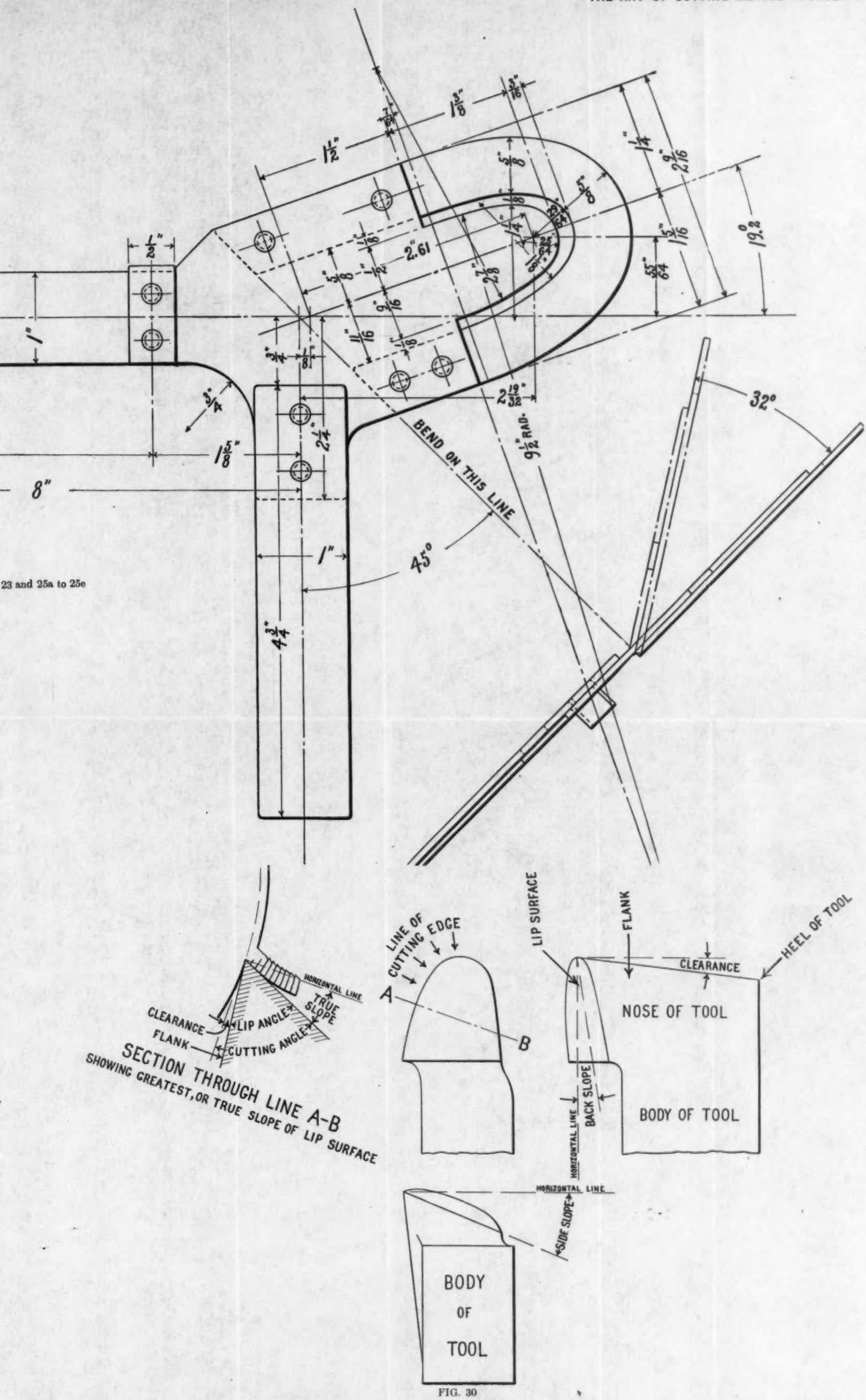


FIG. 30

DEFINITIONS

Drawing showing the meaning of the terms: Body of tool, nose of tool, flank of tool, heel of tool, lip surface of tool, clearance angle, back slope, side slope, true slope, lip angle, cutting angle and line of cutting edge. Tool about two-thirds used up. For drawing of new tool, see Folder 6, Fig. 28 and Folder 5, Fig. 25a

(See index preceding Part 2)

23 and 25a to 25e

FIG. 32

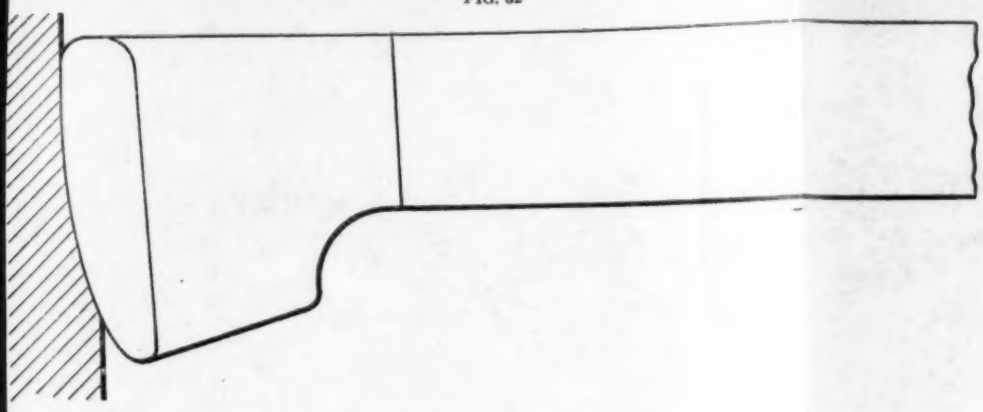
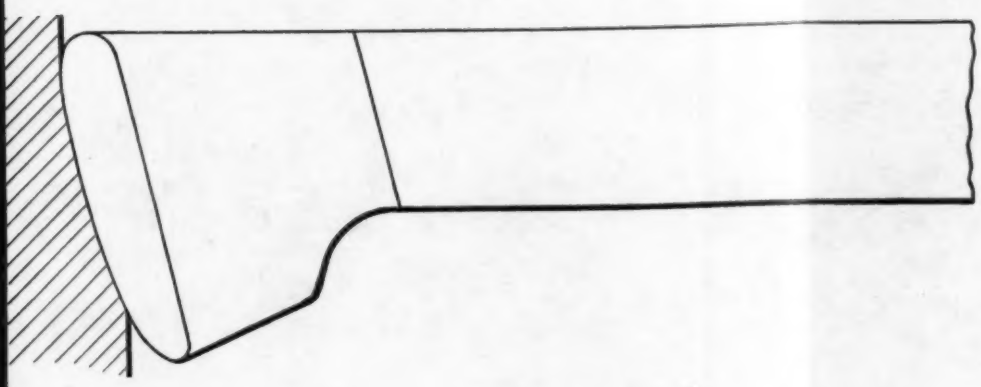


FIG. 33



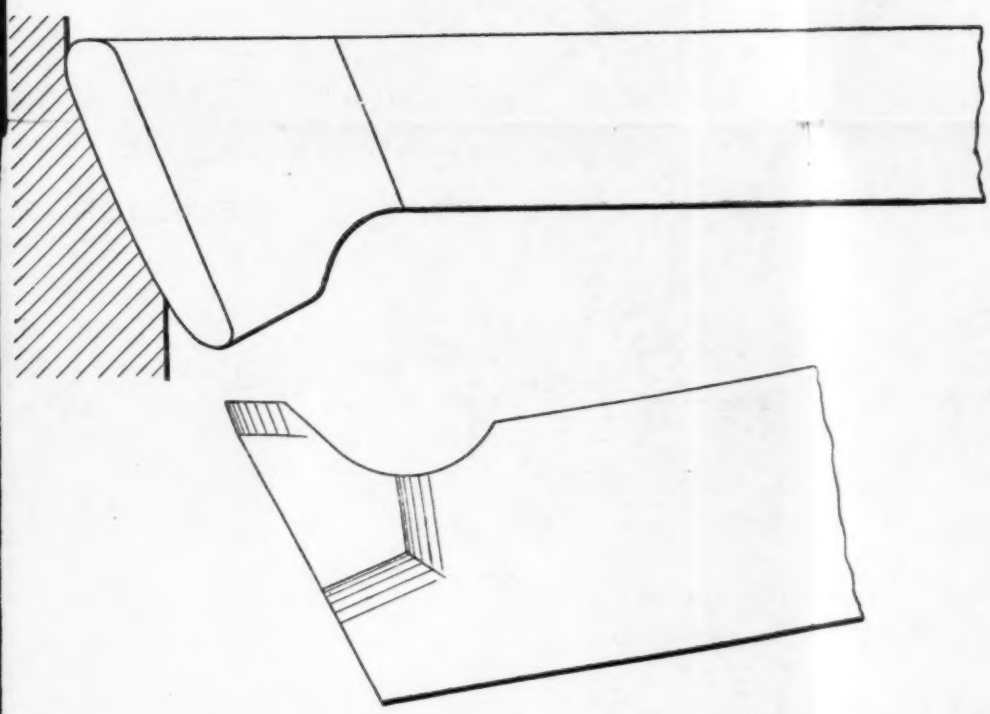
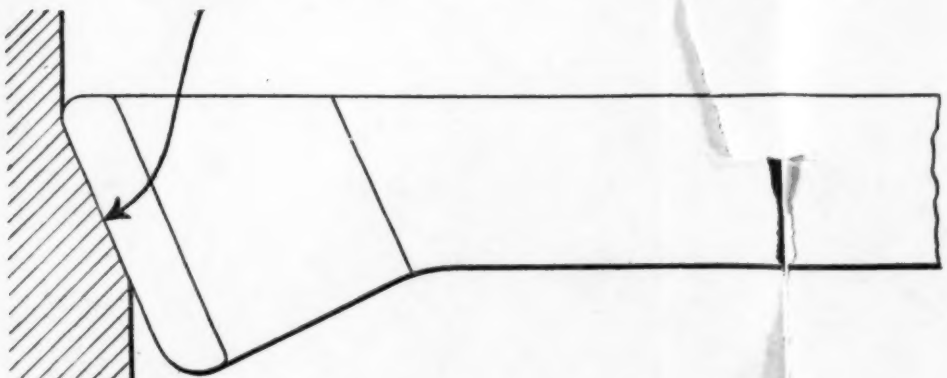


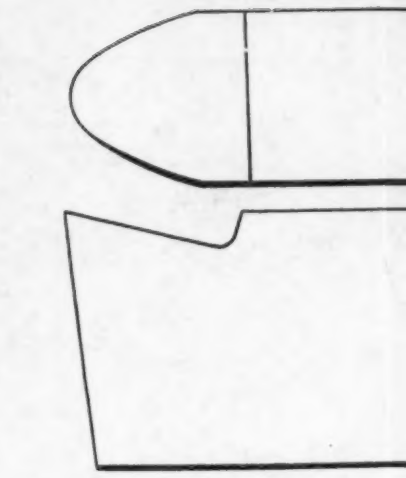
FIG. 34

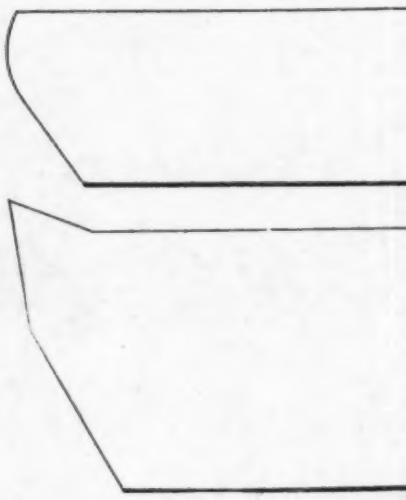
FIGS. 32, 33, 34 BROAD NOSED TOOLS WITH SLIGHTLY CURVED CUTTING EDGES REFERRED TO IN PARAGRAPHS 312 TO 314

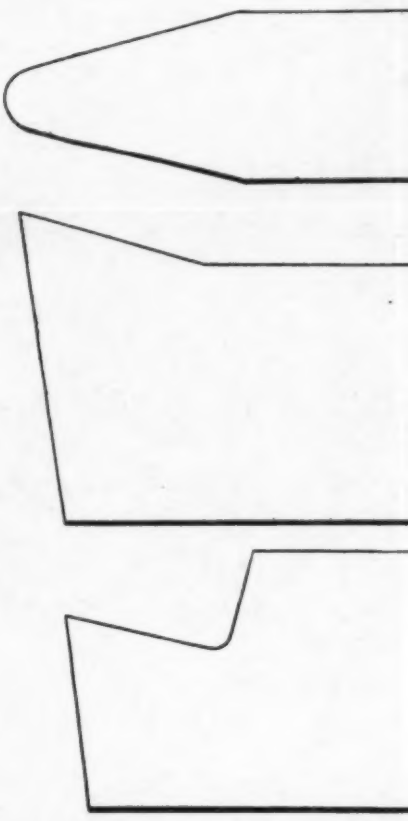
FIG. 35

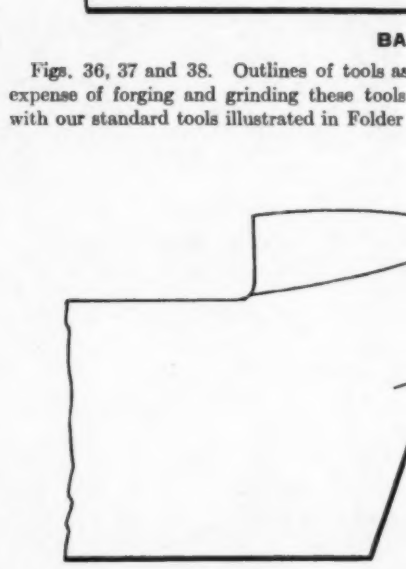
Straight Edge Tool referred to in paragraphs 67 to 71. Exactly one inch of cutting edge under cut











BA

Figs. 36, 37 and 38. Outlines of tools as
expense of forging and grinding these tools
with our standard tools illustrated in Folder

FIG. 39a

Our standard tool after it is about two-thi
used up. Back slope 8°, side slope 14°

SIDE SLOP

Drawing showing that side slope as emb
times before weakening its body than is the

FIG. 36

FIG. 37

FIG. 38

BADLY SHAPED TOOLS

s of tools as improperly dressed and ground in many shops. The combined these tools and the danger of injuring them in grinding is far greater than d in Folder 5, Figs. 21a to 25e. (See paragraphs 431 to 441)

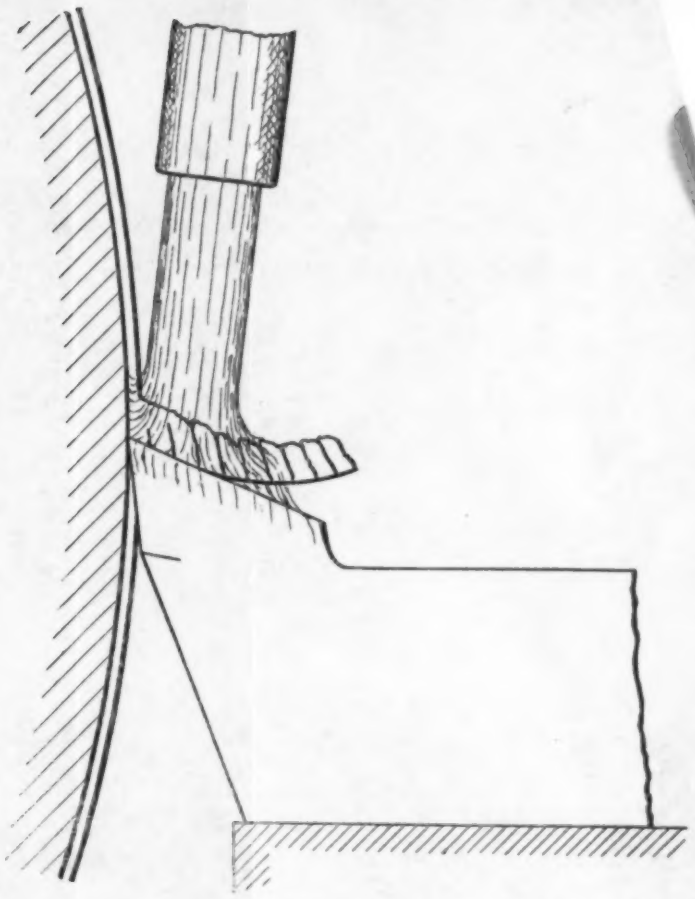


FIG. 40a

DRAWING SHOWING PROPER WAY OF THROWING HEAVY STREAM OF WATER ON TOOL TO COOL IT

This gives an increase in cutting speed of 30 per cent to 40 per cent. (See paragraphs 607 to 609)

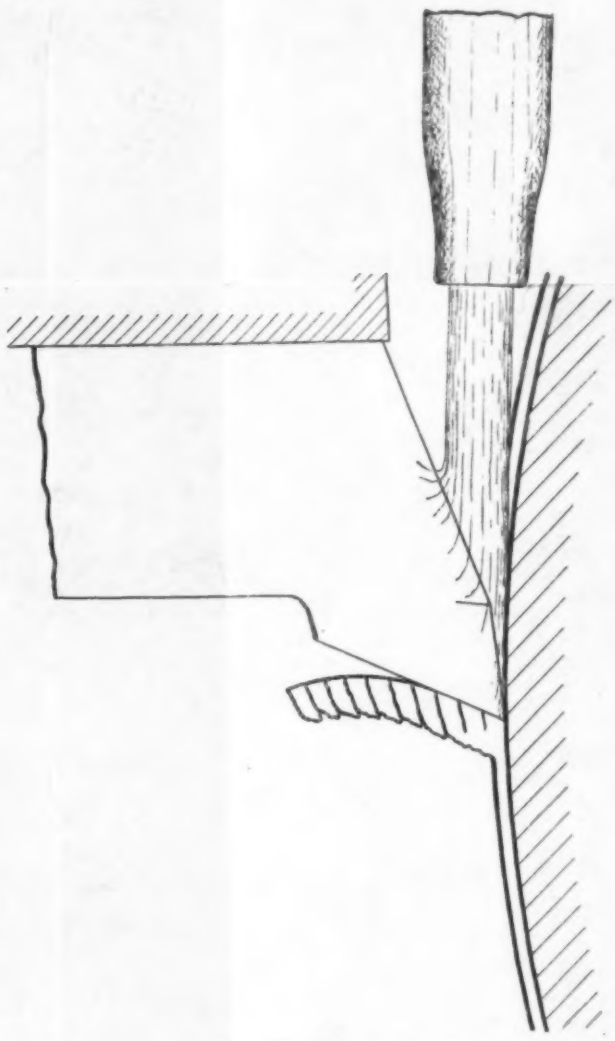


FIG. 40b

DRAWING SHOWING WRONG WAY OF THROWING WATER ON TOOL. (See paragraph 607)

bout two-thirds
de slope 14°

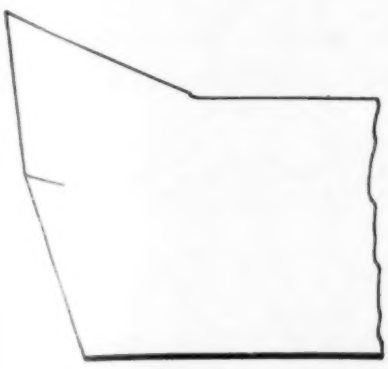


FIG. 39b

Tool having same maximum slope as our standard, but this all obtained by back slope

FIG. 39

DE SLOPE BETTER THAN BACK SLOPE

lope as embodied in our standard tool allows the tool to be ground many more than is the case with a tool having all back slope. (See paragraph 379)

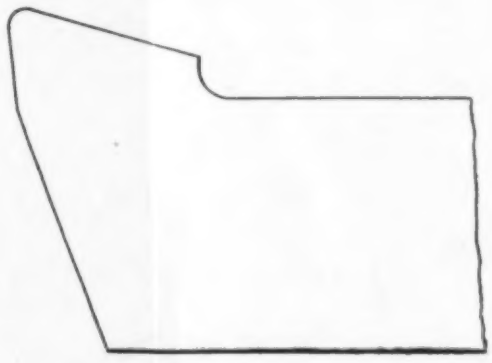


FIG. 41

Showing the extent to which the cutting edge of Carbon Roughing Tools are sometimes rounded over when cutting at standard speeds. The tool when in this condition still continues to work well. (See paragraphs 170 to 174)

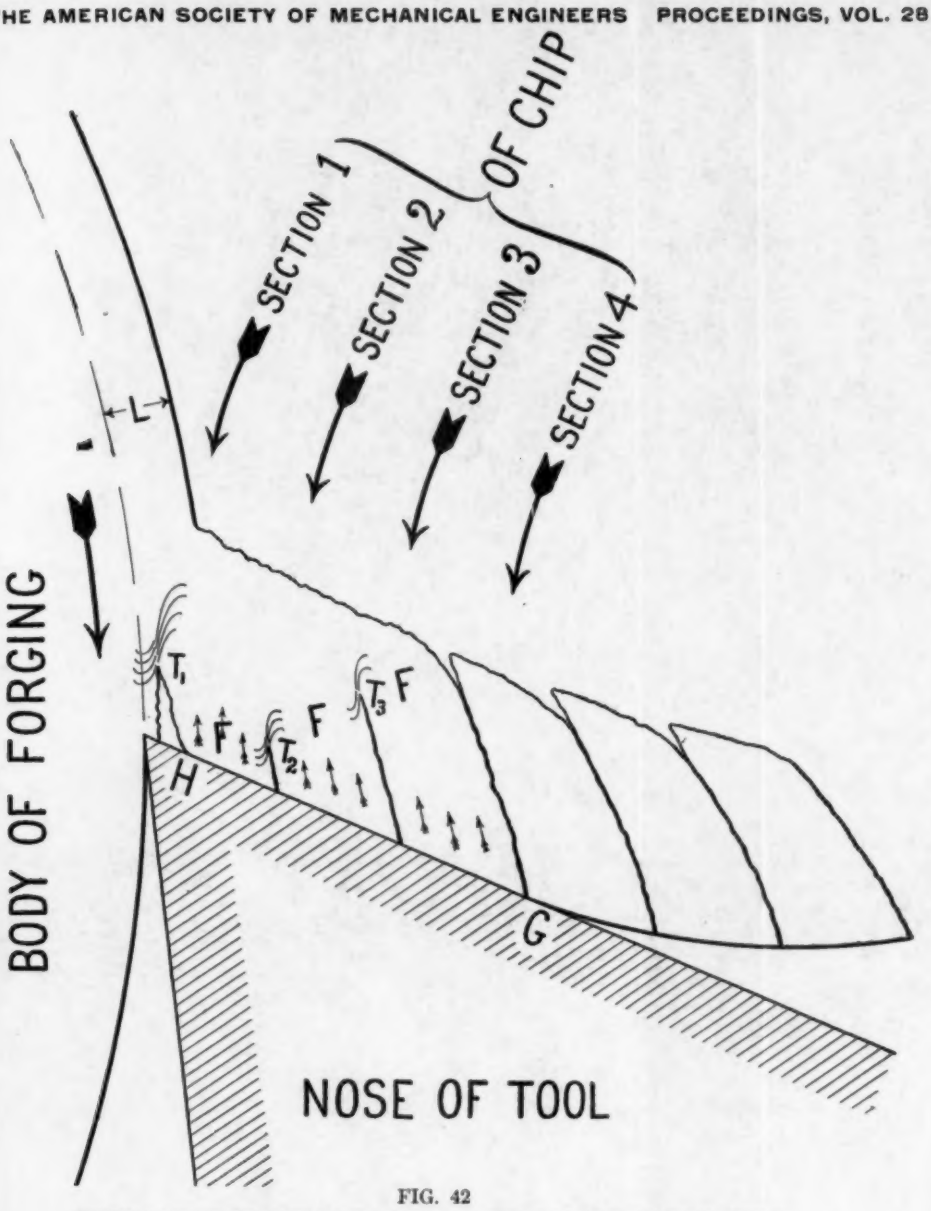


FIG. 42

DRAWING SHOWING HOW CHIP IS PARTLY TORN AND PARTLY SHEARED FROM BODY OF FORGING

Shearing taking place upon at least two lines of cleavage at the same time. Cutting edge of tool not under heavy pressure. (See paragraphs 153 to 169; see Folder 3, Figs. 17c and 17a; see Folder 8, Figs. 43 and 44)

TABLE 45 EFFEC

THIS REPRESI

	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
FEED	1/16" DEPTH OF CUT					1/8" DEPTH OF CUT					3/16" DEPTH OF CUT				
1/16"	65_c	G_1	84.6	20.0	G	58_c	F_8	63.6	20.0	G					
	66_c	G_4	91.7	20.0	G	59_c	G_1	66.6	20.0	G					
	67_c	G_5	100.2	20.0	G	60_c	F_1	73.4	18.0	R					
	68_c	G_6	105.0	5.0	R	61_c	F_2	nick in tool tested							
	69_c	F_8	103.6	5.5	R	62_c	F_9	71.7	20.0	F					
	70_c	F_9	96.0	8.5	R										
	$71c$	F_{10}	103.0	20.0	F										
	Conclusion		103	20	G	Conclusion		72	20	G	Previously Standardized at 60 feet				
1/8"	72_c	G_1	61.1	20.0	G	52_c	K_8	61.0	5.0	R	1_c	K_8	39.6	20.0	G
	73_c	G_7	66.0	12.5	R	53_c	E_2	55.7	7.0	R	2_c	K_5	41.1	14.0	R
	74_c	F_8	65.0	8.5	R	54_c	E_3	47.9	10.0	R	3_c	D_2	42.7	20.0	G
	75_c	F_{10}	65.5	20.0	G	55_c	F_1	44.2	20.0	G	4_c	D_3	44.3	13.5	R
						56_c	F_2	47.3	20.0	F	5_c	D_5	50.3	9.0	R
						57_c	F_3	47.6	8.0	R	6_c	D_8	45.0	20.0	G
						75_c	G_4	48.8	20.0	G					
						76_c	G_3	52.4	10.5	R					
						77_c	G_1	50.3	9.5	R					
	Conclusion		65.5	20	G	Conclusion		48.8	20	G	Conclusion		45	20	G
3/16"	84_c	G_4	57.8	4.5	R	48_c	F_9	45.6	6.0	R	7_c	D_9	29.6	20.0	F
	85_c	G_5	55.9	5.0	R	49_c	F_{10}	38.5	20.0	G	8_c	E_1	29.9	20.0	G
	86_c	K_2	43.1	12.0	R	50_c	G_1	43.2	11.0	R	9_c	E_2	34.9	20.0	G
	87_c	K_3	43.4	20.0	G	51_c	G_2	42.8	15.0	R	10_c	E_4	38.2	11.0	R
	88_c	K_4	46.3	20.0	G						11_c	E_3	38.5	11.5	R
	89_c	N_1	46.5	6.0	R						12_c	RF_{111}	47.0	13.5	R
	90_c	N_2	47.1	20.0	G										
	91_c	N_3	49.9	10.0	R										
	Conclusion		47.1	20	G	Conclusion		40	20	G	Conclusion		35	20	G

STANDARD ROUND NOSE ROUGHING TOOL ¾". CLEARANCE 6°, BACK SL

For Logarithmic Plot and Summary Table of these experi

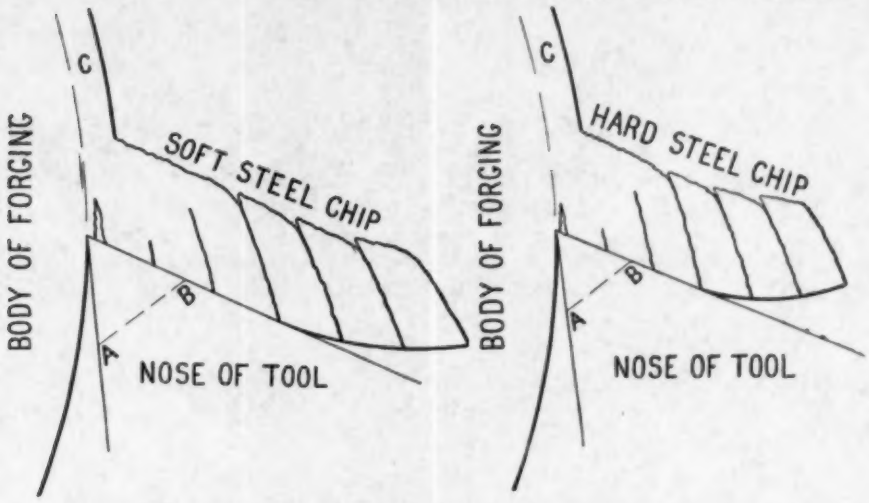
Date and Place of Experiments: THE BETHLEHEM

CHEMICAL COMPOSITION OF TOOL NO. 27
FOLDER 20, TABLE 138

Tungsten	8.50
Chromium	2.00
Carbon	1.85
Manganese	0.15
Silicon	0.15
Phosphorus	
Sulphur	

CHEMICAL COMPOSITION OF FORGING

Carbon	0.33
Manganese	0.63
Silicon	
Phosphorus	0.31
Sulphur	0.172



HOW HARD AND SOFT STEEL CHIPS BEAR UPON LIP SURFACE OF TOOL

FIGS. 43 and 44

Drawing showing that a soft steel chip bears upon a much larger area of the lip surface of the tool than a hard steel chip and explaining why, with a heavier total pressure of the soft steel chip, still the cutting speed is much faster than for a hard steel chip; and this because the center of the pressure of a hard steel chip thus being closer to the cutting edge of the tool, and its intensity greater, the heat generated is much more concentrated toward the point of the tool where the sectional area that must carry off this heat is much less. (See paragraphs 516 to 519, also paragraphs 506 to 519)

45 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN CUTTING STEEL

See paragraphs 259, 782 to 785

REPRESENTS ONE OF THE MOST SUCCESSFUL SERIES OF EXPERIMENTS MADE BY US

DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
CUT		¼″ DEPTH OF CUT					⅜″ DEPTH OF CUT					½″ DEPTH OF CUT				
		19_c	K_5	43.4	20.0	G	33_c	F_6	39.7	20.0	F	79_c	K_{10}	tool broke in ¼ min.		
		20_c	D_2	49.9	20.0	G	34_c	F_1	41.2	20.0	G	80_c	K_4	39.4	20.0	G
		21_c	E_1	54.0	12.5	R	35_c	F_2	42.2	20.0	G	81_c	I_3	45.0	11.0	R
		22_c	E_2	48.3	12.0	R	36_c	F_1	43.4	20.0	G	82_c	G_1	40.5	15.5	R
		23_c	E_7	51.6	20.0	F	37_c	F_2	50.6	12.5	R	83_c	G_4	43.3	20.0	G
							38_c	F_3	49.0	20.0	N.R					
at 60 feet		Conclusion		51.6	20	6	Conclusion		49	20	6	Conclusion		43.3	20	6
20.0	G	24_c	E_9	38.5	15.5	R	39_c	D_2	29.0	20.0	G					
14.0	R	25_c	E_{10}	37.6	20.0	F	40_c	E_7	33.9	10.0	R					
20.0	G	26_c	K_3	38.4	15.5	R	41_c	E_{10}	33.9	20.0	G					
13.5	R	78_c	I_1	39.9	13.5	R	42_c	F_1	35.8	19.75	R					
9.0	R															
20.0	G															
20	6	Conclusion		37.6	20	6	Conclusion		34.6	20	6					
20.0	F	13_c	K_8	broke in 3 min.			43_c	D_3	24.8	20.0	G					
20.0	G	14_c	D_3	28.3	20.0	F	44_c	F_8	broke in 12.5 min.							
20.0	G	15_c	E_1	30.4	20.0	F	45_c	F_7	29.1	9.0	R					
11.0	R	16_c	D_8	32.4	12.0	R	46_c	E_{10}	26.4	10.5	R					
11.5	R	17_c	E_2	30.8	20.0	G	47_c	F_3	25.8	14.0	R					
13.5	R	18_c	D_9	33.0	7.0	G										
20	6	Conclusion		30.8	20	6	Conclusion		24.8	20	6					

°, BACK SLOPE 8°, SIDE SLOPE 14°. See FOLDER 5, FIGS. 24 and 20b

these experiments, see Folder 18, Figs. 127, 128 and 129

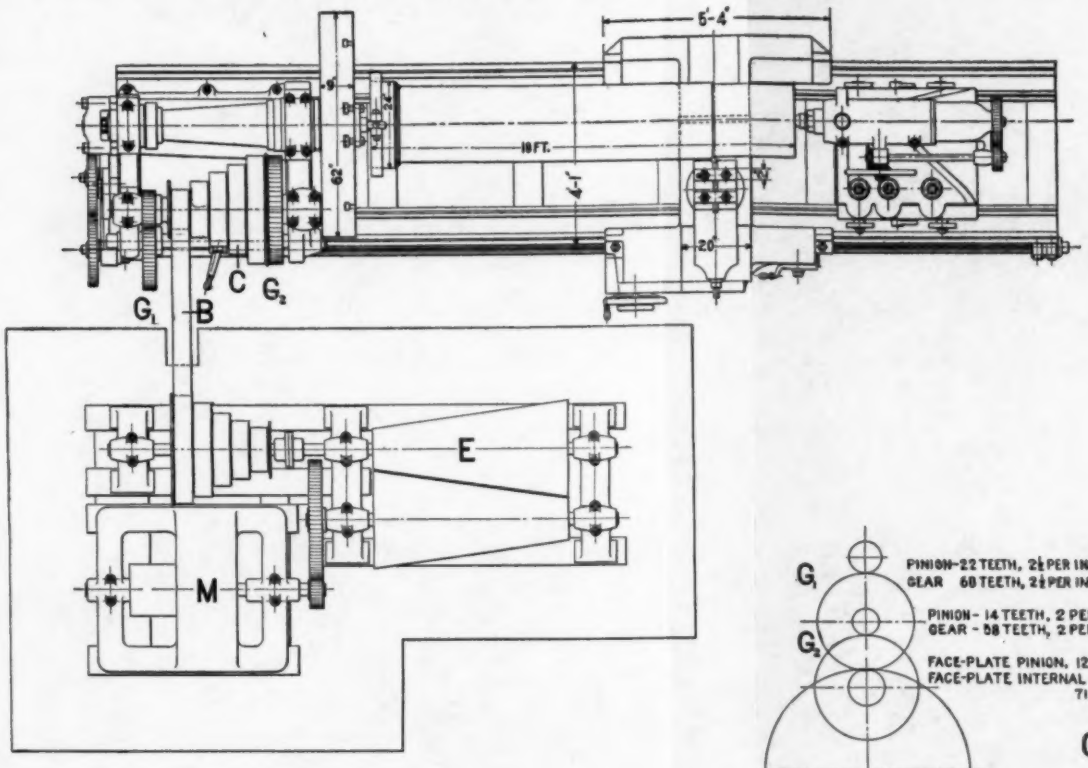
BETHLEHEM STEEL COMPANY, BETHLEHEM, PA., 1900

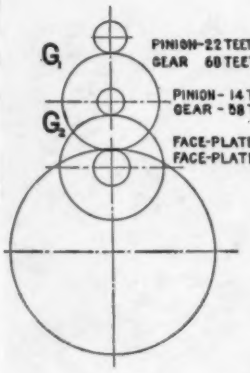
PHYSICAL PROPERTIES

Tensile Strength.....67365
Elastic Limit.....39545
Per Cent Extension.....25.25
Per Cent Contraction.....45.565

MEANING OF FOLLOWING SYMBOLS

G—Good
F—Fair
BR—Began to Ruin
R—Ruined



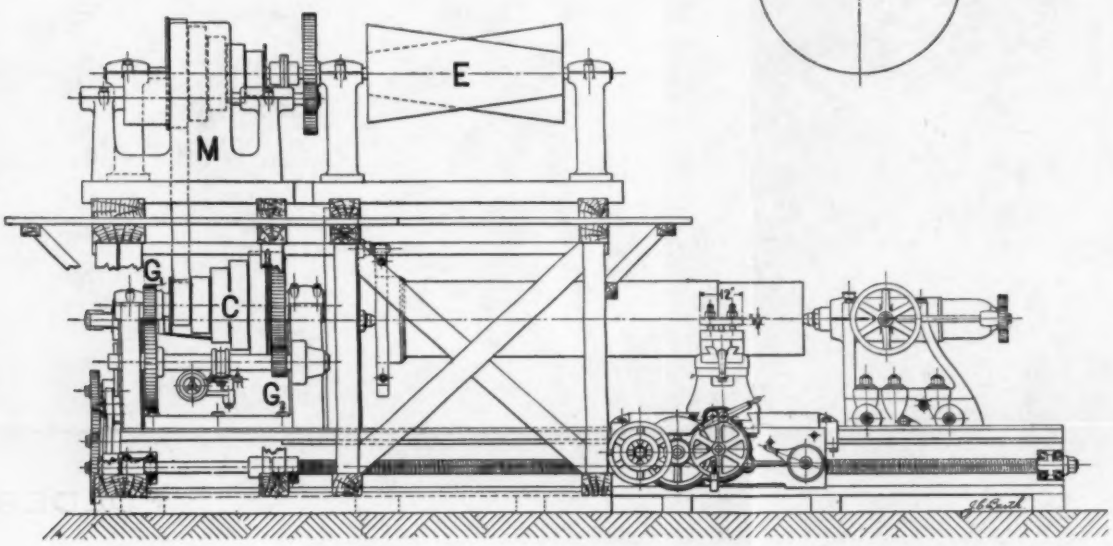


PINION-22 TEETH, 2½ PER INCH, 8.8" PITCH DIAM., 3½" FACE.
GEAR 68 TEETH, 2½ PER INCH, 27.2" PITCH DIAM., 3½" FACE.

PINION - 14 TEETH, 2 PER INCH, 7" PITCH DIAM., 3½" FACE.
GEAR - 58 TEETH, 2 PER INCH, 29 PITCH DIAM., 3½" FACE.

FACE-PLATE PINION, 12 TEETH, 1¼ PER INCH, 9.6" PITCH DIAM., 5" FACE.
FACE-PLATE INTERNAL GEAR,
71 TEETH, 1¼ PER INCH, 56.8" PITCH DIAM., 5" FACE.

GEAR TRAIN.



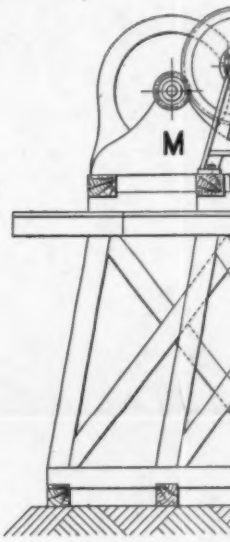


FIG. 50

EXPERIMENTAL LATHE AT THE WORKS OF THE BETHLEHEM STEEL COMPANY

We believe that, for determining the laws of cutting metals, a lathe at least as large and massive as this should be used and that it should of obtaining any desired speed. (See paragraph 228, also 217 to 228)

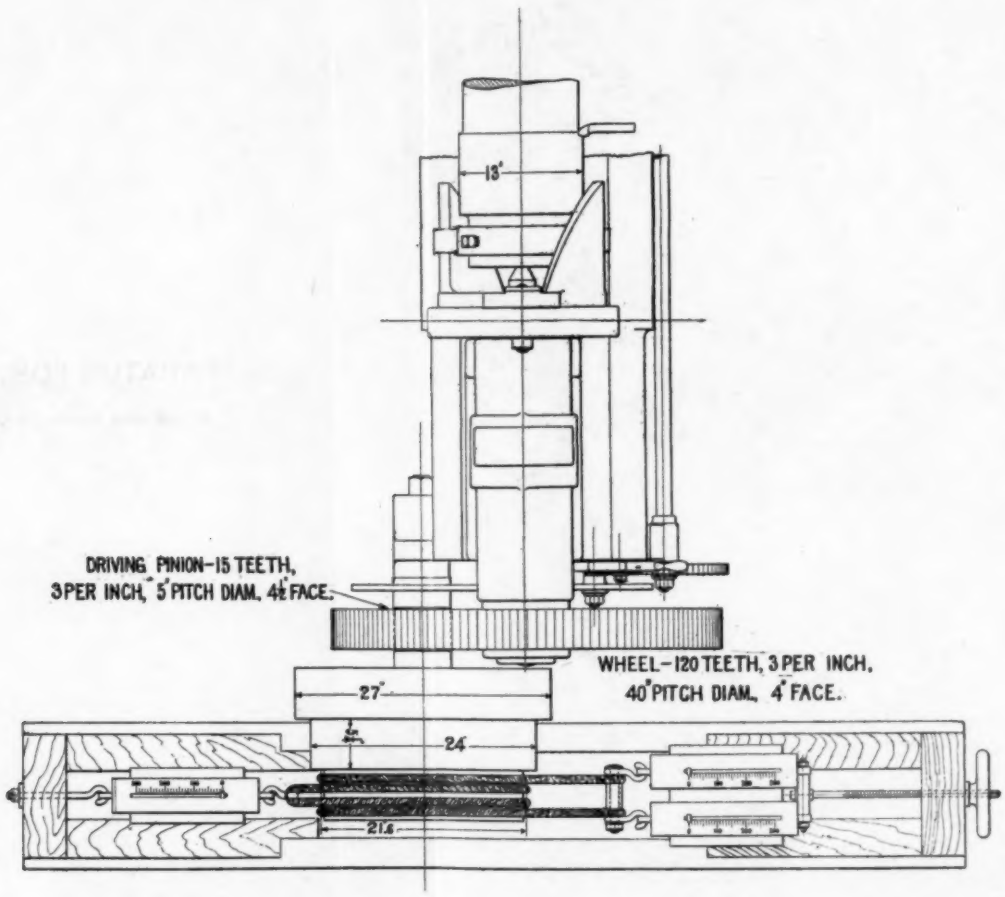


FIG. 51

Drawing of Lathe used in Determining the P

Showing rope brake with spring balances at each end by means of which the driving force of the lathe was weighed. Experim

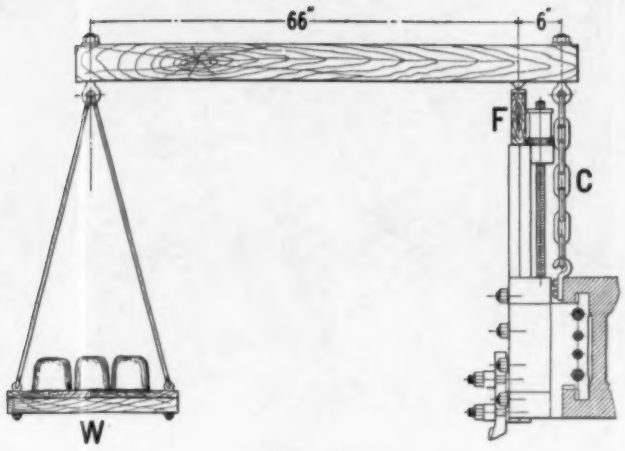


FIG. 52

APPARATUS USED IN EXPERIMENTS FOR MEASURING PRESSURE REQUIRED TO FEED A TOOL.

Experiments made with Tool in Vertical Slide of an 84" Boring Mill, showing that machines should be designed so as to give a Feeding Pressure equal to the Driving Pressure on a Tool. (See paragraph 585, also 581 to 585; also see Folder 12, Fig. 83.)

Place and Date of Experiments: MIDVALE STEEL CO., PHILADELPHIA, PA., 1883

M., 5'FACE.
AM., 5'FACE.

CUT-METER.

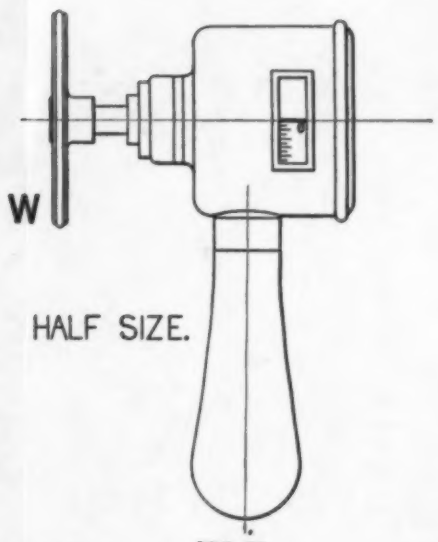
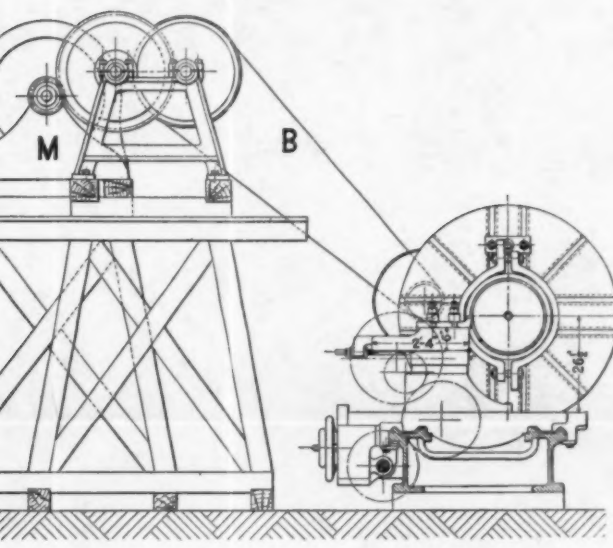


FIG. 53

Instrument for quick determination of approximate cutting speed; needs no stop watch. (See Folder 9, Fig. 54, and paragraphs 234 to 236)



COMPANY

at it should have positive feeds and positive means
8)

ROTAMETER

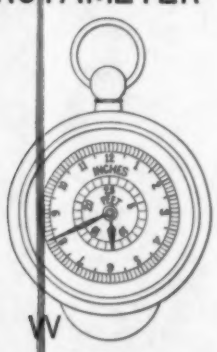


FIG. 54

Instrument for determining cutting speed in making experiments; requires the use of a watch. (See Folder 9, Fig. 53, and paragraphs 230 to 233)

DEPTH OF CUT GAUGE.

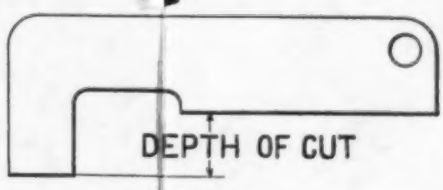


FIG. 55

This is the best instrument for maintaining the depth of the cut uniform in making experiments. (See paragraphs 238 to 241)

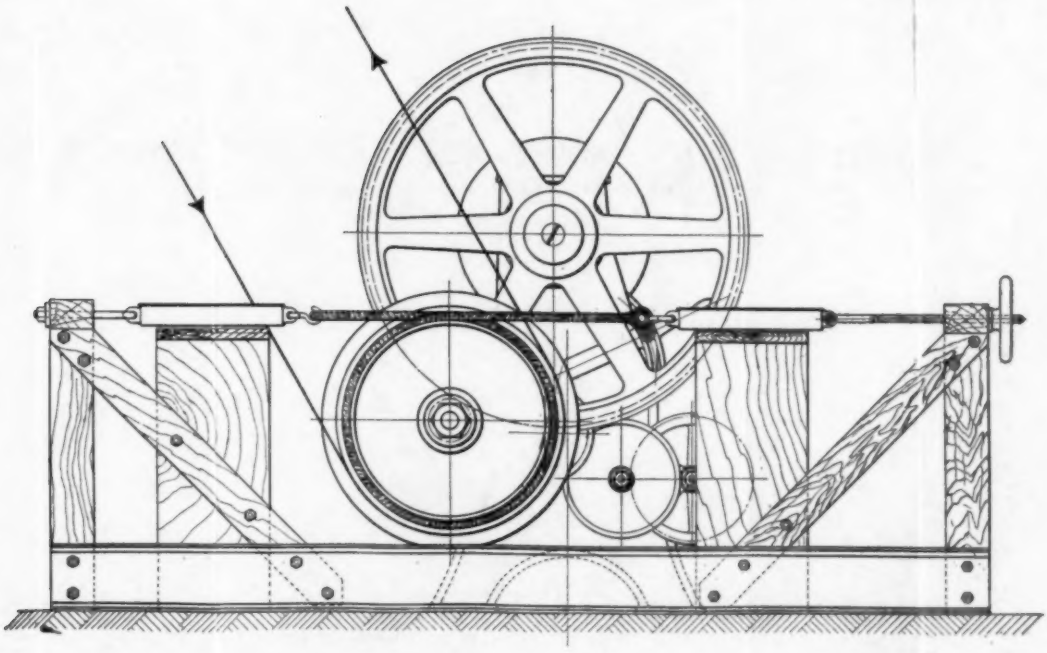
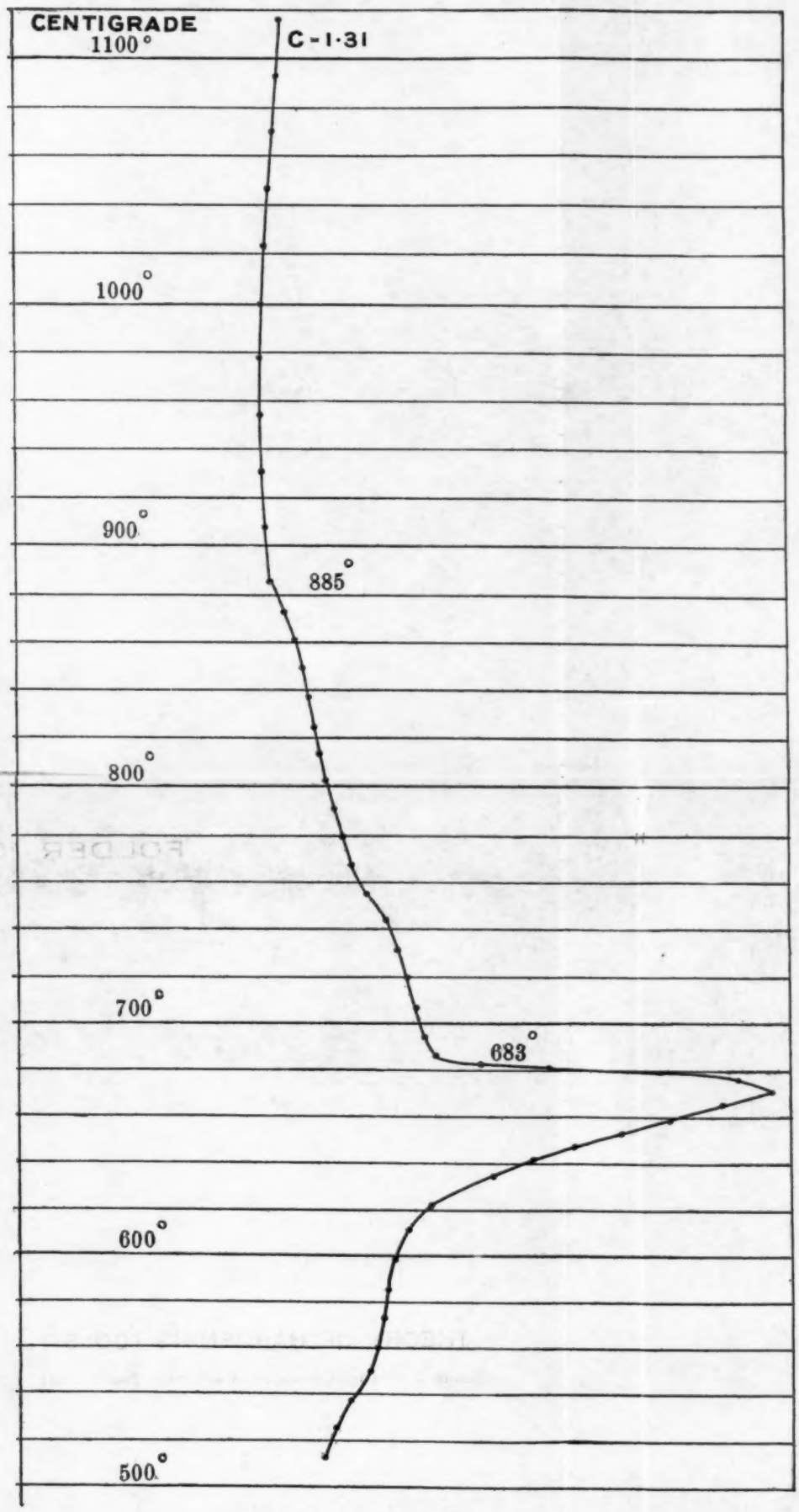
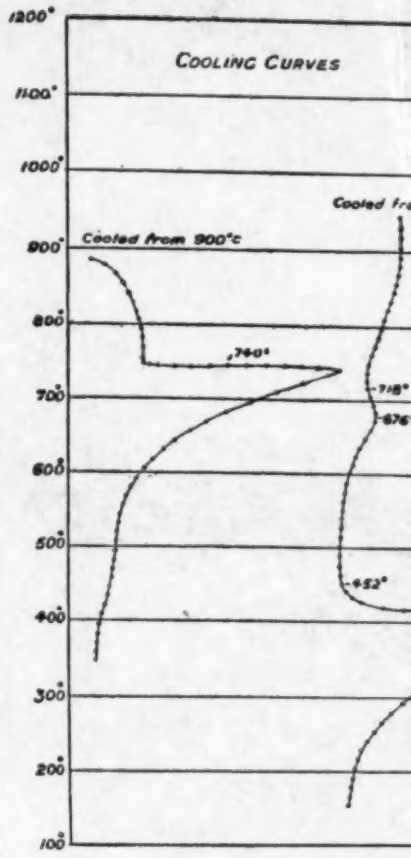


FIG. 51

ng the Pressure of the Chip on the Tool

Experiments made in the shop of Wm. Sellers & Co., Inc., Philadelphia, Pa., in 1902. (See paragraphs 531 to 534)





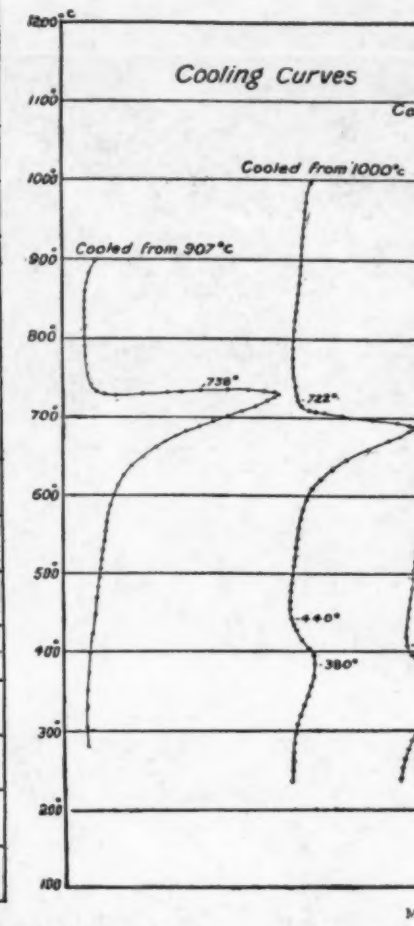


FIG. 56

FIGS. 56, 57 and 58 Cooling and Heating Curves Showing the Critical Points or Points of Recalesence in Carb

See paragraphs 1110 to 1116

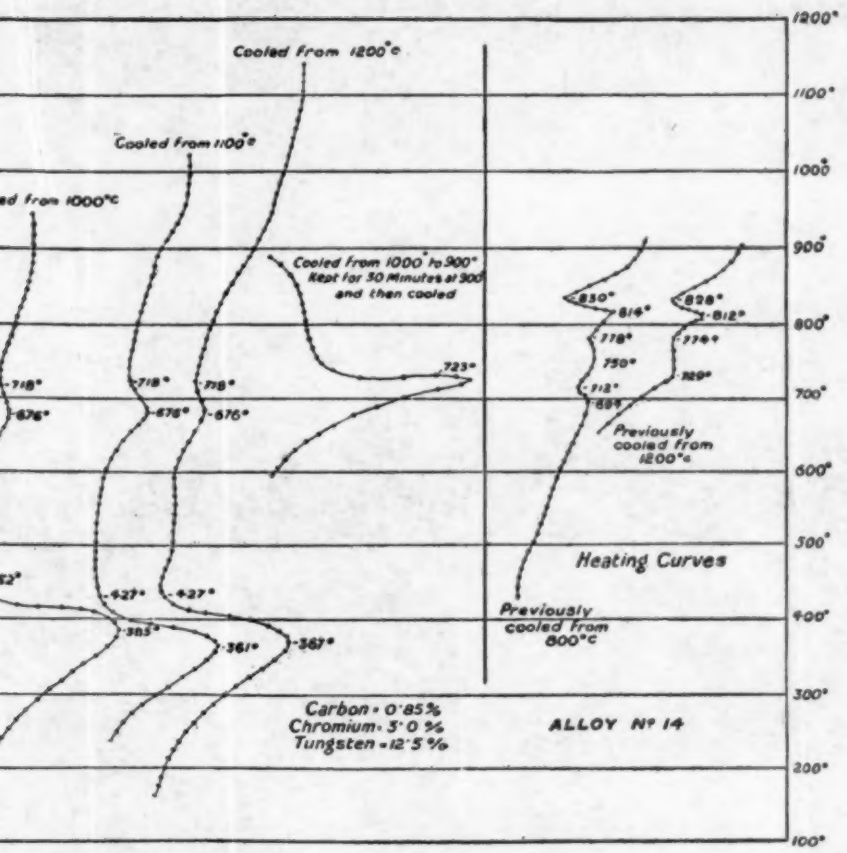
Fig. 56 is the cooling curve of carbon steel of the same composition as ordinary tool steel

See paragraph 1110

Fig. 57 and Fig. 58 Give the heating c
high speed tool steels

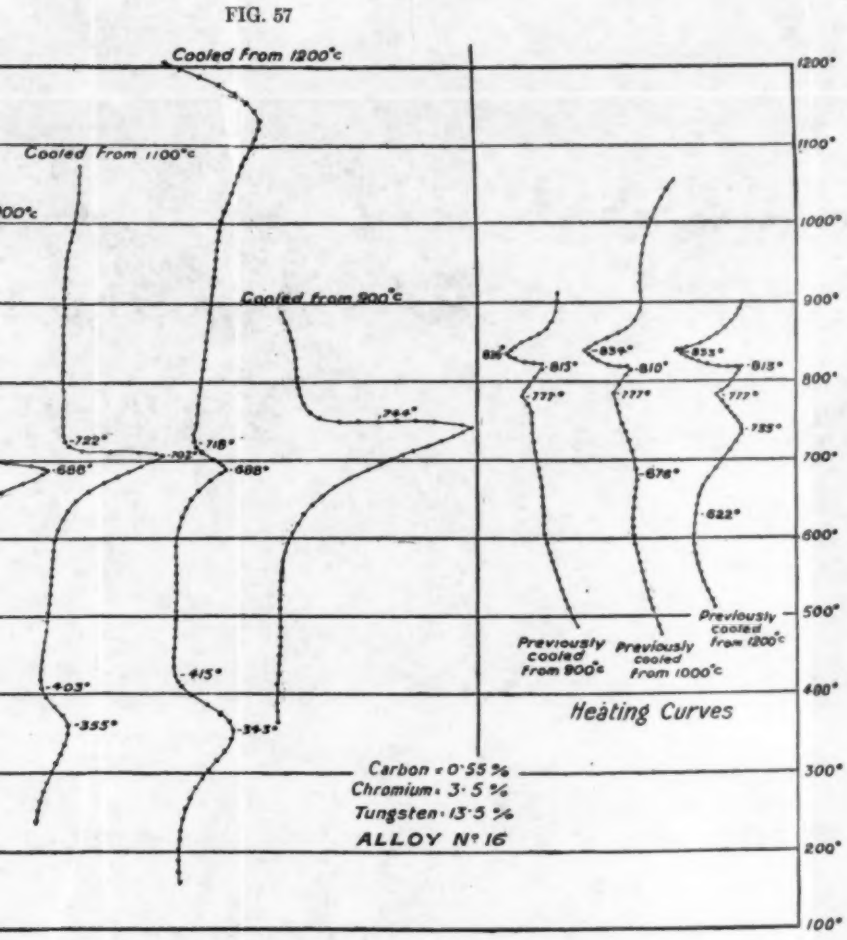
The effect of heating these steels beyon
properties of high speed tools begin to be p

Experiments made by Prof. H. C. H. C



MOVEMENTS OF THE DIFFERENTIAL GALVANOMETER, $\frac{1}{12}$TH SIZE.

FIG. 57



MOVEMENTS OF THE DIFFERENTIAL GALVANOMETER, $\frac{1}{12}$TH SIZE.

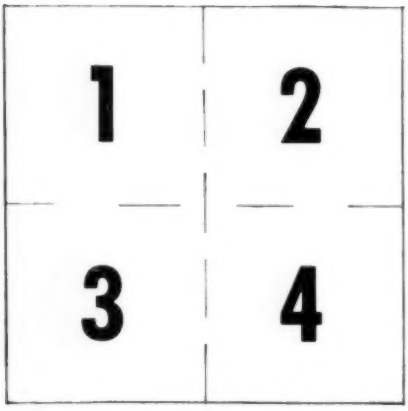
FIG. 58

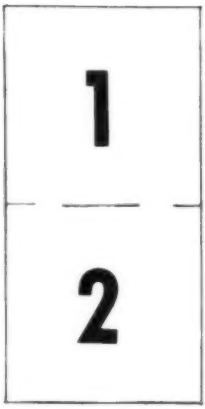
Carbon Tool Steel and in High Speed Steels of Two Different Analyses

ting curves on the right of the vertical line and the cooling curves on the left for two different modern

beyond (940° C.) 1725° Fahr. (the point indicated by our experiments at which the remarkable
o be produced), is clearly shown by the change at the critical points of the cooling curves
. H. CARPENTER, M.A., PH.D., OF MANCHESTER, ENGLAND

Maps on this order too large to be
are filmed clockwise beginning in th
right and top to bottom as many fra
diagrams illustrate the method.





o be entirely included in one exposure
in the upper left hand corner, left to
ny frames as required. The following

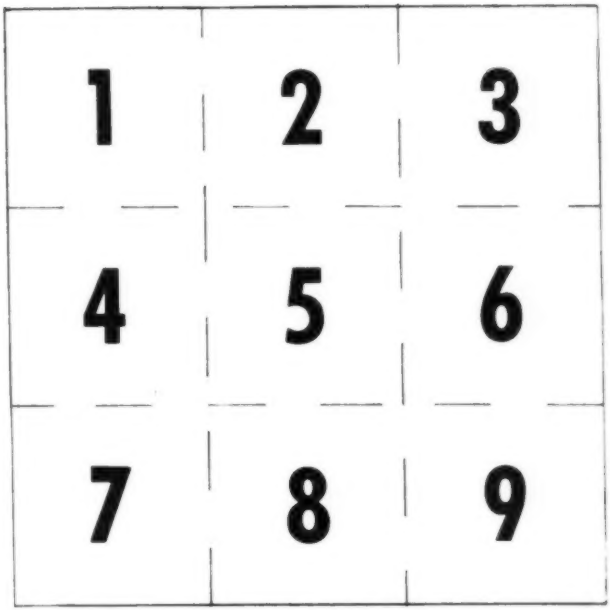


TABLE 75 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN CUTTING STEEL

This represents one of the poorest of any of our sets of experiments from which we have attempted to draw any conclusions

See paragraph 261

DEPTH OF CUT IN INCHES	EXPERIMENT NUMBER	FEED IN INCHES	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
1/12	708	0.0197	TW8	160.3	20.4	G.
	709	0.0198	TW11	175.0	5.6	B.R.
	710	0.0199	TW6	166.2	3.4	B.R.
	711	0.0200	TW9	166.2	3.8	B.R.
	712	0.0200	TW3	163.0	4.3	B.R.
	713	0.0203	TW7	161.9	20.0	G.
	TOOLS ALL REGROUND 1/16" OFF.					
	719	0.0205	TW7	165.5	14.2	B.R.
	720	0.0206	TW9	164.7	20.0	G.
	721	0.0201	TW6	171.5	11.6	G.end
	722	0.0203	TW3	177.9	7.7	B.R.
	Conclusion			Feed 0.0204	165	20.0 / 6
1/8	690	0.0184	TW8	135.0	20.0	G.
	691	0.0188	TW2	147.5	12.8	B.R.
	692	0.0204	TW3	141.6	16.4	G.end
	693	0.0197	TW6	145.0	7.3	B.R.
	694	0.0197	TW8	143.0	20.0	G.
	Conclusion			Feed 0.0197	143	20.0 / 6
3/16	665	0.0189	TW9	88.4	20.0	G.
	666	0.0178	TW10	101.0	14.1	F.end
	667	0.0187	TW11	102.6	20.0	G.
	668	0.0196	TW7	110.0	20.0	F.
	669	0.0190	TW12	120.6	14.9	B.R.
	Conclusion			Feed 0.019	114	20.0 / 6
5/32	735	0.0200	TW7	97.4	15.2	B.R.
	736	0.0204	TW3	97.0	8.1	B.R.
	737	0.0207	TW6	96.8	13.8	B.R.
	738	0.0206	TW11	91.2	20.0	G.
	739	0.0206	TW9	95.8	20.0	G.
	740	0.0206	TW11	100.1	20.0	G.
	741	0.0196	TW9	108.8	20.0	G.
	742	0.0206	TW11	118.9	14.3	G.end
	743	0.0204	TW9	131.0	6.7	B.R.
	Conclusion			Feed 0.02	114	20.0 / 6

DEPTH OF CUT IN INCHES	EXPERIMENT NUMBER	FEED IN INCHES	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
1/12	702	0.0313	TW7	125.0	17.0	G.end
	703	0.0317	TW9	129.5	5.8	B.R.
	704	0.0317	TW10	125.5	2.6	B.R.
	705	0.0317	TW11	127.0	18.1	B.R.
	706	0.0318	TW3	121.9	20 0	G.
	707	0.0319	TW7	125.3	20.0	G.
	Conclusion			Feed 0.0319	125.5	20.0 / 6
1/8	685	0.0298	TW10	104.2	10.3	B.R.
	686	0.0299	TW2	100.3	20.0	G.
	687	0.0293	TW3	109.6	20.0	G.
	688	0.0294	TW5	118.9	8.0	B.R.
	689	0.0294	TW6	112.6	18.2	B.R.
	Conclusion			Feed 0.0295	111	20.0 / 6
3/16	663	0.0306	TW6	71.4	20.0	G.
	664	0.0310	TW8	78.6	13.9	B.R.
	672	0.0310	TW3	75.2	20.0	G.
	673	0.0309	TW5	80.0	20.0	F.
	674	0.0303	TW9	85.4	20.0	G.
	675	0.0302	TW11	89.6	9.7	B.R.
	676	0.0307	TW10	89.8	7.0	B.R.
	Conclusion			Feed 0.0303	85.5	20.0 / 6
5/32	730	0.0322	TW6	75.0	18.7	B.R.
	731	0.0323	TW8	75.0	20.0	G.
	732	0.0326	TW11	83.4	20.0	G.
	733	0.0327	TW9	91.6	12.2	B.R.
	734	0.0322	TW8	92.0	5.8	B.R.
	Conclusion			Feed 0.032	85	20.0 / 6

DEPTH OF CUT IN INCHES	EXPERIMENT NUMBER	FEED IN INCHES	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
1/12	698	0.0463	TW7	92.0	23.7	G.end
	699	0.0455	TW8	99.8	20.0	G.
	700	0.0450	TW3	109.6	5.1	B.R.
	701	0.0461	TW6	104.9	10.5	B.R.
	Conclusion			Feed 0.0454	100	20.0 / 6
1/8	680	0.0455	TW5	79.5	15.5	B.R.
	681	0.0455	TW6	84.9	7.6	B.R.
	682	0.0462	TW7	72.8	20.0	G.
	683	0.0456	TW9	76.1	20.0	G.
	684	0.0460	TW11	80.4	16.5	B.R.
	Conclusion			Feed 0.0454	78	20.0 / 6
3/16	661	0.0454	TW3	61.5	20.0	G.
	662	0.0466	TW5	67.0	14.1	B.R.
	670	0.0466	TW2	64.6	20.0	G.
	671	0.0460	TW6	70.1	12.0	B.R.
	Conclusion			Feed 0.0466	64.6	20.0 / 6
5/32	723	0.0462	TW10	54.8	8.4	B.R.
	724	0.0454	TW8	50.4	20.0	G.
	725	0.0467	TW11	54.8	20.0	G.
	726	0.0468	TW9	60.0	20.0	G.
	727	0.0467	TW7	65.0	18.1	B.R.
	728	0.0465	TW3	65.4	11.2	B.R.
	729	0.0462	TW10	55.0	13.1	B.R.
	Conclusion			Feed 0.0466	64	20.0 / 6

STANDARD ROUND NOSE ROUGHING TOOL, ¾" x 1". CLEARANCE ANGLE 6°, BACK SLOPE 8°, SIDE SLOPE 14°. See Folder 5, Figs. 21b an

Place and Date of Experiments: WM. SELLERS & CO., PHILADELPHIA, PA., 1902

CHEMICAL COMPOSITION OF FORGING

Carbon	0.34
Manganese	0.60
Silicon	0.183
Phosphorus	0.035
Sulphur	0.032

PHYSICAL PROPERTIES OF FORGING

Annealed at 1275°

Tensile Strength	71300
Elastic Limit	32590
Per Cent Extension	29.00
Per Cent Contraction	49.57

CHEMICAL COMPOSITION OF TOOL No. 27. FOLDER 21, TABLE 38, FIG. 139

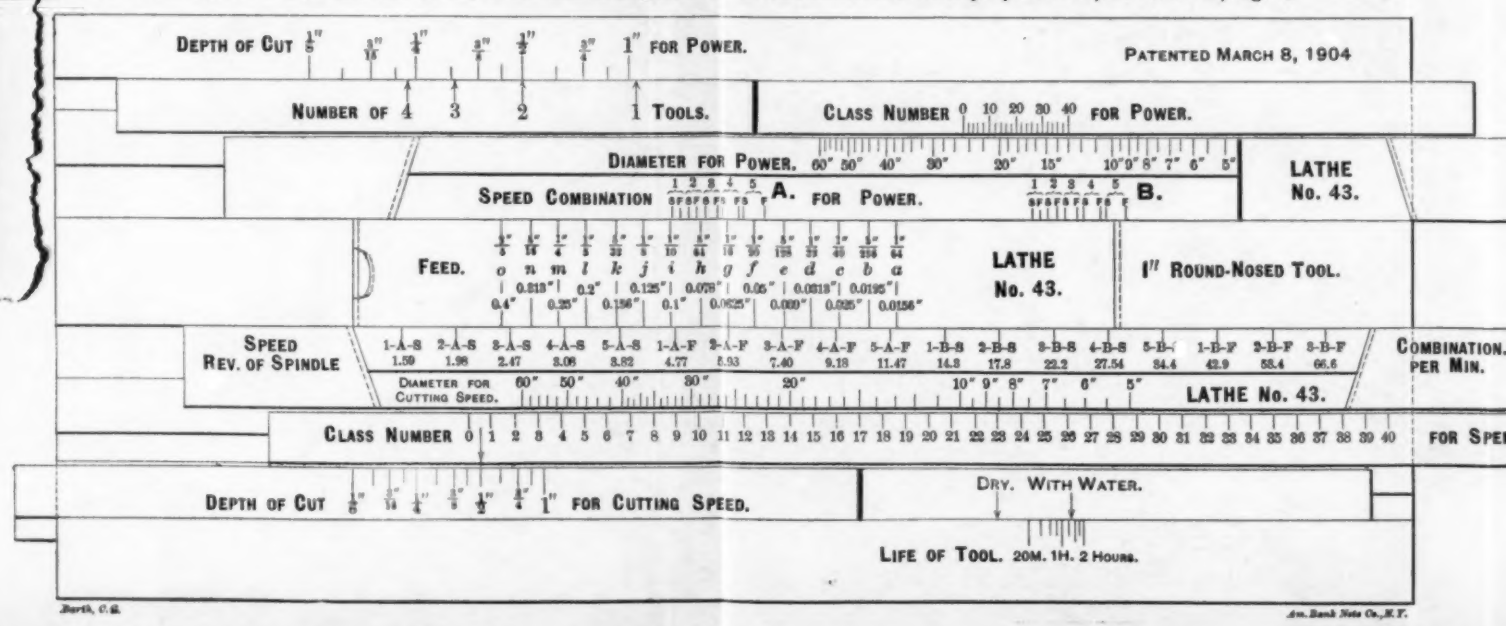
Tungsten	8.50
Chromium	2.00
Carbon	1.85
Manganese	0.15
Silicon	0.15
Phosphorus	
Sulphur	

MEANING OF FOLLOWING

G— Good
F— Fair
BR— Began to
R— Ruined

Fig. 79 Slide Rule Embodying the Important Laws Deduced by Us

This Slide Rule formed the principal subject of Mr. Barth's paper, "Slide Rules for the Machine Shop as a Part of the Taylor System of Management," forming part XXV of the Transactions of The American Society of Mechanical Engineers. For time slide rule to accompany this rule, see Folder 11, Fig. 78


DEPTH OF CUT 1/8" 1/16" 1/4" 3/8" 1/2" 3/4" 1" FOR POWER.
PATENTED MARCH 8, 1904
NUMBER OF 4 3 2 1 TOOLS.
CLASS NUMBER 0 10 20 30 40 FOR POWER.
DIAMETER FOR POWER. 60" 50" 40" 30" 20" 15" 10" 9" 8" 7" 6" 5"
LATHE No. 43.
SPEED COMBINATION 1 2 3 4 5 A. FOR POWER. B.
FEED. o n m l k j i h g f e d c b a
LATHE No. 43.
1" ROUND-NOSED TOOL.
SPEED REV. OF SPINDLE
1-A-S 2-A-S 3-A-S 4-A-S 5-A-S 1-A-F 2-A-F 3-A-F 4-A-F 5-A-F 1-B-S 2-B-S 3-B-S 4-B-S 5-B-S 1-B-F 2-B-F 3-B-F
1.59 1.98 2.47 3.08 3.82 4.77 5.93 7.40 9.18 11.47 14.3 17.8 22.2 27.54 34.4 42.9 53.4 66.6
COMBINATION. PER MIN.
DIAMETER FOR CUTTING SPEED. 60" 50" 40" 30" 20" 10" 9" 8" 7" 6" 5"
LATHE No. 43.
CLASS NUMBER 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
FOR SPEE
DEPTH OF CUT 1/8" 1/16" 1/4" 3/8" 1/2" 3/4" 1" FOR CUTTING SPEED.
DRY. WITH WATER.
LIFE OF TOOL. 20M. 1H. 2 HOURS.

Barth, C.E. Am. Bank Note Co., N.Y.

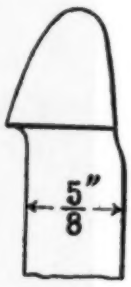
	EXPERIMENT NUMBER	FEED IN INCHES	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
nd	695	0.0638	TW10	73.0	17.9	B.R.
	696	0.0641	TW11	70.6	20.0	G.
	697	0.0636	TW9	77.6	10.3	B.R.
	Conclusion		**Feed 0.064**	**71**	**20.0**	**G**
	677	0.0637	TW8	61.0	20.0	G.
	678	0.0636	TW2	68.7	13.8	B.R.
	679	0.0636	TW3	65.2	19.5	B.R.
	Conclusion		**Feed 0.0636**	**64.5**	**20.0**	**G**
	660	0.0646	TW2	53.3	12.0	B.R.
	RUNS ON FORGING No. 6					
	609	0.0625	TW11	50.6	12.1	G,end
	610	0.0625	TW6	49.9	16.5	G.end
	613	0.0625	TW7	51.3	13.2	B.R.
	748	0.0654	TW3	55.2	9.9	G.end
	749	0.0656	TW4	55.7	15.5	B.R.
	750	0.0658	TW5	55.8	10.9	G.end
	751	0.0654	TW6	55.8	14.5	B.R.
	752	0.0654	TW8	55.4	15.2	B.R.
	753	0.0638	TW7	55.4	16.0	F.end
	754	0.0638	TW10	54.5	10.7	B.R.
	Conclusion		**Feed 0.063**	**54**	**20.0**	**G**

Figs. 21b and 25c

FOLLOWING SYMBOLS

Good
Fair
– Began to ruin
Ruined

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°



forming part of Volume

COMBINATION.
PER MIN.

FOR SPEED.

TABLE 76 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN

This table gives the actual cuts taken by the tools in this series of experiments, and rep
the best sets of experiments made by us in turning cast iron

For summary of this and other similar experiments, see Folder 19, Fig. 134. See paragraphs 26

DEPTH OF CUT IN INCHES	FEED 0".0156					FEED 0".0316					FEED 0".0632			
	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES
3/32	1475	BS22	121.2	7.2	BR	1472	BS22	90.4	14.0	BR	1467	BS22	61.3	20.0
	1476	BS20	112.4	6.5	BR						1469	BS20	65.5	10.2
	1477	BS13	112.4	6.8	BR						1470	BS20	63.3	6.3
	1478	BS22	105.0	21.4	G						1474	BS20	63.0	7.7
	1479	BS22	112.0	22.2	G									
	Conclusion		**112**	**20**	**G**	**Conclusion**		**87**	**20**	**G**	**Conclusion**		**61**	**20**
3/16	1446	BS11	90.0	20.7	G	1443	BS11	70.2	20.0	F	1436	BS6	45.0	20.0
	1447	BS11	90.0	20.0	G	1444	BS6	70.2	12.4	BR	1437	BS10	50.0	12.3
	1448	BS6	90.0	10.4	BR	1445	BS10	70.2	9.0	BR	1438	BS11	50.3	25.0
	1450	BS12	90.5	19.8	G						1439	BS12	55.4	5.3
	1451	BS11	95.0	10.4	BR						1440	BS12	55.4	7.2
											1459	BS22	49.9	20.0
											1460	BS20	49.9	19.1
	Conclusion		**90.5**	**20**	**G**	**Conclusion**		**70**	**20**	**G**	**Conclusion**		**50**	**20**
3/8											1461	BS22	38.5	25.1
											1462	BS20	41.1	22.2
											1468	BS11	42.2	17.8
											1471	BS13	40.3	20.0
											1473	BS13	43.5	11.4
	Conclusion					**Conclusion**					**Conclusion**		**41.5**	**20**

STANDARD ROUND NOSE ROUGHING TOOL, $\frac{3}{4}$" x $1\frac{1}{2}$". CLEARANCE ANGLE 6°, BACK SLOPE 8°, SIDE SLOPE 14°.

Place and Date of Experiments: WM. SELLERS & CO., INC., PHILADELPHIA, PA., 19

Tool heated to melting point and cooled in air blast

CHEMICAL COMPOSITION OF TOOL
No. 20. Folder 20, Table 138

Tungsten	14.71
Chromium	2.90
Carbon	0.70
Manganese	0.12
Silicon	0.196
Phosphorus	0.017
Sulphur	0.01

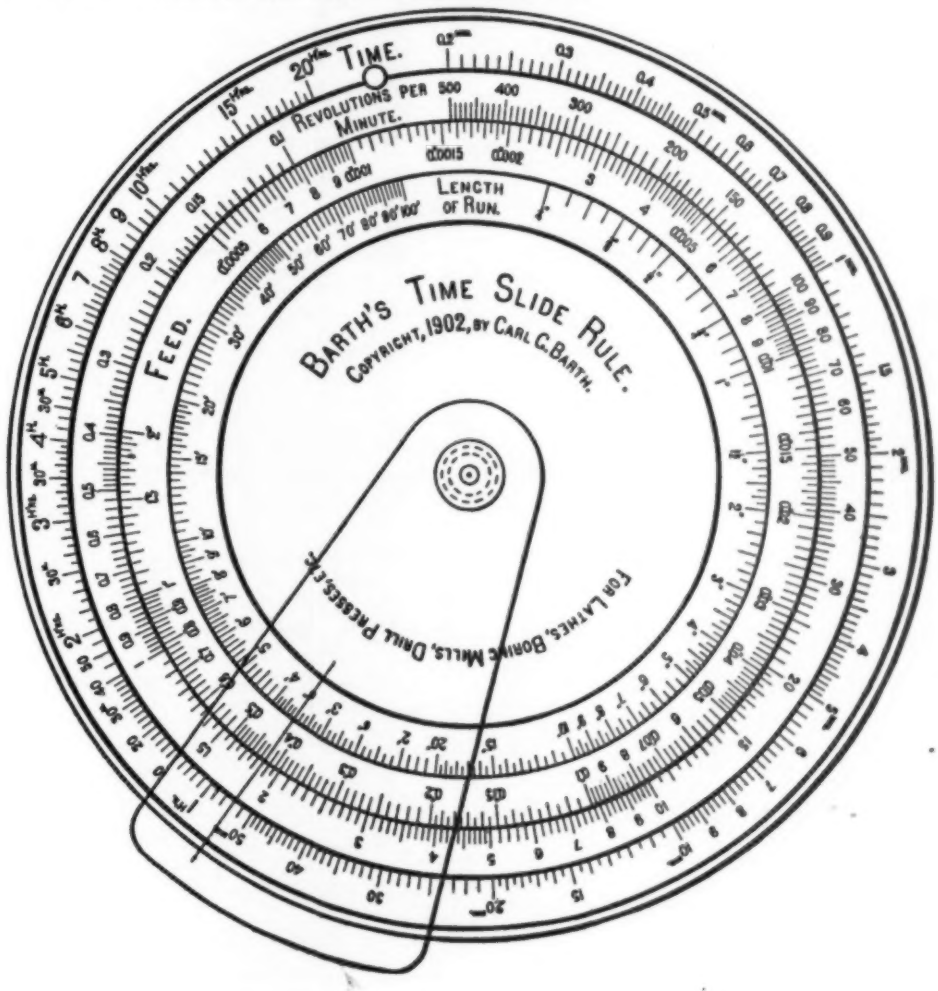
CHEMICAL COMPOSITION OF TEST PIECE

Combined Carbon	
Graphite	
Manganese	
Silicon	1.1
Phosphorus	
Sulphur	

MEANIN

FIG. 78 TIME SLIDE RULE FOR MACHINE SHOP USE

This slide rule is described by Mr. Barth in his paper on slide rules, and is used in connection with lathe slide rule shown in Folder 11 Fig. 79 to determine length of time required to take a given cut from the feed and revolutions per minute obtained with lathe slide rule.



EL

FEED IN INCHES	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
0.0638	TW10	73.0	17.9	B.R.
0.0641	TW11	70.6	20.0	G.
0.0636	TW9	77.6	10.3	B.R.
usion	Feed 0.064	71	20.0	6
0.0637	TW8	61.0	20.0	G.
0.0636	TW2	68.7	13.8	B.R.
0.0636	TW3	65.2	19.5	B.R.
usion	Feed 0.0636	64.5	20.0	6
0.0646	TW2	53.3	12.0	B.R.
RUNS ON FORGING No. 6				
0.0625	TW11	50.6	12.1	G,end
0.0625	TW6	49.9	16.5	G.end
0.0625	TW7	51.3	13.2	B.R.
0.0654	TW3	55.2	9.9	G.end
0.0656	TW4	55.7	15.5	B.R.
0.0658	TW5	55.8	10.9	G.end
0.0654	TW6	55.8	14.5	B.R.
0.0654	TW8	55.4	15.2	B.R.
0.0638	TW7	55.4	16.0	F.end
0.0638	TW10	54.5	10.7	B.R.
sion	Feed 0.063	54	20.0	6

d 25c

SYMBOLS

ruin

of Volume

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°

TABLE 76 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED I

This table gives the actual cuts taken by the tools in this series of experiments, and r
the best sets of experiments made by us in turning cast iron

For summary of this and other similar experiments, see Folder 19, Fig. 134. See paragraphs

DEPTH OF CUT IN INCHES	FEED 0".0156					FEED 0".0316					FEED 0".0632			
	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT
3/32	1475	BS22	121.2	7.2	BR	1472	BS22	90.4	14.0	BR	1467	BS22	61.3	20
	1476	BS20	112.4	6.5	BR						1469	BS20	65.5	10
	1477	BS13	112.4	6.8	BR						1470	BS20	63.3	6
	1478	BS22	105.0	21.4	G						1474	BS20	63.0	7
	1479	BS22	112.0	22.2	G									
	Conclusion		112	20	6	Conclusion		87	20	6	Conclusion		61	2
3/16	1446	BS11	90.0	20.7	G	1443	BS11	70.2	20.0	F	1436	BS6	45.0	20
	1447	BS11	90.0	20.0	G	1444	BS6	70.2	12.4	BR	1437	BS10	50.0	12
	1448	BS6	90.0	10.4	BR	1445	BS10	70.2	9.0	BR	1438	BS11	50.3	25
	1450	BS12	90.5	19.8	G						1439	BS12	55.4	5
	1451	BS11	95.0	10.4	BR						1440	BS12	55.4	7
											1459	BS22	49.9	20
											1460	BS20	49.9	19
	Conclusion		90.5	20	6	Conclusion		70	20	6	Conclusion		50	2
3/8											1461	BS22	38.5	25
											1462	BS20	41.1	22
											1468	BS11	42.2	17
											1471	BS13	40.3	20
											1473	BS13	43.5	11
	Conclusion					Conclusion					Conclusion		41.5	2

STANDARD ROUND NOSE ROUGHING TOOL, $\frac{3}{4}$" x $1\frac{1}{2}$". CLEARANCE ANGLE 6°, BACK SLOPE 8°, SIDE SLOPE

Place and Date of Experiments: WM. SELLERS & CO., INC., PHILADELPHIA, P

Tool heated to melting point and cooled in air blast

CHEMICAL COMPOSITION OF TOOL
No. 20. Folder 20, Table 138

Tungsten	14.71
Chromium	2.90
Carbon	0.70
Manganese	0.12
Silicon	0.196
Phosphorus	0.017
Sulphur	0.01

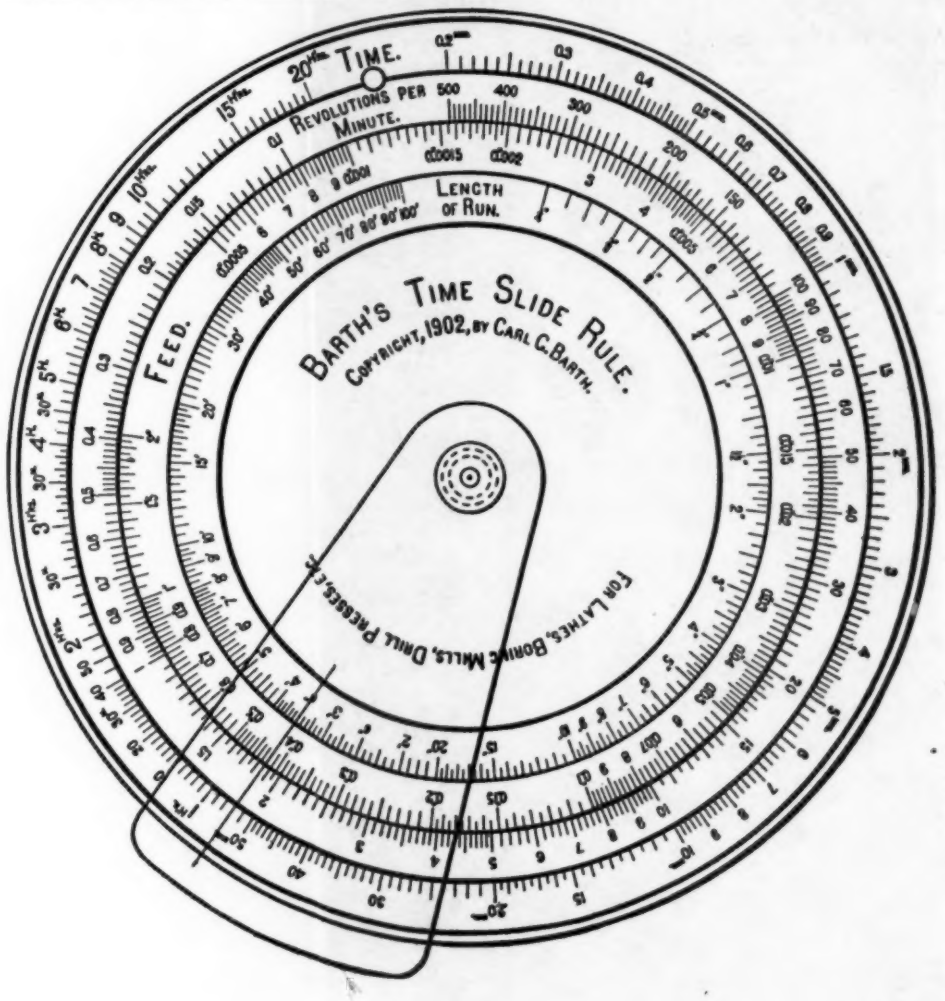
CHEMICAL COMPOSITION OF TEST PIECE

Combined Carbon	
Graphite	
Manganese	
Silicon	1.1
Phosphorus	
Sulphur	

ME

FIG. 78 TIME SLIDE RULE FOR MACHINE SHOP USE

This slide rule is described by Mr. Barth in his paper on slide rules, and is used in connection with lathe slide rule shown in Folder 11 Fig. 79 to determine length of time required to take a given cut from the feed and revolutions per minute obtained with lathe slide rule.



ID FEED IN CUTTING HARD CAST IRON
nents, and represents one of
ast iron
e paragraphs 260, 805

SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET PER MINUTE	DURATION OF CUT IN MINUTES	CONDITION OF TOOL
D 0".0632					FEED 0".127		
61.3	20.0	G	1481	BS6	45.4	12.2	F
65.5	10.2	BR	1482	BS11	47.6	12.4	BR
63.3	6.3	BR					
63.0	7.7	BR					
61	20	6	Conclusion		43	20	6
45.0	20.0	G	1423	BS3	35.4	4.7	BR
50.0	12.3	BR	1424	BS5	30.1	20.0	F
50.3	25.0	G	1426	BS6	29.8	20.0	G
55.4	5.3	BR	1427	BS10	31.9	13.0	BR
55.4	7.2	BR	1428	BS11	31.9	16.4	G
49.9	20.0	BR	1429	BS5	32.2	3.9	BR
49.9	19.1	BR	1430	BS6	32.2	20.0	F
			1431	BS10	30.3	20.0	F
			1432	BS11	32.2	20.0	G
			1433	BS12	35.1	16.8	G
50	20	6	Conclusion		32	20	6
38.5	25.1	G					
41.1	22.2	BR					
42.2	17.8	G					
40.3	20.0	G					
43.5	11.4	G					
41.5	20	6	Conclusion				

SIDE SLOPE 14°. See Folder 5, Figs. 21a and 25b
ADELPHIA, PA., 1903.

MEANING OF FOLLOWING SYMBOLS

G— Good
F— Fair
BR—Began to ruin
R— Ruined

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°

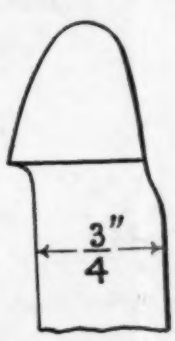


FIG. 77 SAMPLE SHEET FOR MAKING DAILY RECORDS OF EXPERIMENTS, TWO-THIRDS SIZE

See paragraph 258

EXPERIMENTS ON CUTTING SPEEDS.

PLACE OF EXPERIMENTS: William Sellers & Co. Philadelphia YEAR 1902 MONTH 6th OPERATOR: Carl G. Barth.

SIZE OF SHANK OF TOOL 7/8" × 1 1/8". ~~CASTING~~ FORGING NUMBER 6

ANGLES OF TOOL.	CLEARANCE.	BACK SLOPE.	SIDE SLOPE.
	6°	8°	14°

ACTUAL OUTLINE OF CUTTING EDGE OF TOOL.

CHEMICAL COMPOSITION.	Comb. C	C	Mn	Si	P	S	
		0.30	0.62	0.19	0.035	0.032	
PYSICAL PROPERTIES.	TENSILE STRENGTH	ELASTIC LIMIT.	% ELONGATION.	% CONTRACTION.			
	70300	33940	30.00	48.73			
CHEMICAL COMPOSITION OF TOOL.	W	CH	C	Mn	Si	P	S
	8.50	2.00	1.85	0.15	0.15		

EXPERIMENT NUMBER	DAY OF EXPERIMENTS	DEPTH OF CUT, IN INCHES	FEED, IN INCHES	CUTTING SPEED AIMED AT, IN FEET PER MIN.	AVERAGE CUTTING SPEED OBTAINED	DURATION OF CUT	CONDITION OF TOOL AT END OF RUN	WITH OR WITHOUT WATER	MARK ON TOOL	DIAM. AT TOP OF CUT	DIAM. AT BOT. OF CUT	CUT STARTED FROM END A OR B OF BAR	TIME CUT BEGAN	TIME CUT ENDED	TOTAL TRAVEL OF TOOL
1967	13th	3/16	1/16	60	60.2	20m	Good	Dry	TW15	13 1/4"	12 7/8"	15 1/8"	8 32	8 52	21 11/16"
			Tool guttered some on lip surface												
1968	-"-	-"-	-"-	70	69.9	15.31	Began to ruin	-"-	TW16	-"-	-"-	36 7/8"	8 52	9 10.3	19 1/4"
		Tone chatter during the first 6 minutes								Lip surface guttered some					
1969	-"-	-"-	-"-	65	65.3	20m	Fair	-"-	TW17	-"-	-"-	56 1/4"	9 16	9 36	29 13/32"
		Tool guttered considerably on lip surface													
1970	-"-	-"-	-"-	63				-"-	TW18	-"-	-"-	79 15/16"	9 41		

TABLE 80 PRESSURE ON TOOL IN CUTTING CAST IRON

Table showing that no direct proportion exists: Between the Cutting Speed and the Pressure on the Tool
Between the Cutting Speed and the Crushing or Tensile Strength of
Between the Pressure on the Tool and the Tensile Strength
For shape of tool used in Wm. Sellers & Co. experiments, see Fold

The most important data will be found in the four columns with heavy faced type

See paragraphs 520 and 522

WHERE EXPERIMENTS WERE MADE	KIND OF MATERIAL CUT BY THE TOOL	KIND OF TOOL USED	AIMED AT		ACTUAL SECTIONAL AREA OF CHIP IN SQUARE INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A CUT 3/16" DEEP 1/16" FEED	PRESSURE OF CHIP ON TOOL IN TONS (2000 LBS) PER SQ. INCH SECTIONAL AREA OF CUT	PHYSICAL TESTS OF THE METALS EXPERIMENTED UPON	
			DEPTH OF CUT IN INCHES	FEED IN INCHES				TENSILE STRENGTH IN TONS (2000 LBS) PER SQ. IN.	CRUSHING STRENGTH IN TONS (2000 LBS) PER SQ. IN.
MANCHESTER, ENG. IN 1900 See paragraph 491	SOFT CAST IRON	MISCELLANEOUS MODERN ENGLISH HIGH SPEED CHROMIUM-TUNGSTEN OR MOLYBDENUM TOOLS HEATED TO MELTING POINT	3/16	1/16	0.0124	100	53	6.35	30
	MEDIUM CAST IRON		3/16	1/16	0.0115	49	94	12.50	49
	HARD CAST IRON		3/16	1/16	0.01173	32	92	8.92	47
WM. SELLERS & CO. PHILADELPHIA, PA. IN 1902 See paragraph 525	SOFT CAST IRON BELOW THE OUTSIDE SCALE ROLL 13" DIA. CAST SOLID	HIGH SPEED	3/16	1/16		148	52		
	SAME BAR OF CAST IRON. CUTTING THE SCALE	CHROMIUM-TUNGSTEN HEATED TO MELTING POINT	3/16	1/16		76	52		
	HARD CAST IRON 13" DIA. CONTAINING 15% STEEL SCRAP CAST 2" THICK HOLLOW CENTER	COMPOSITION OF THESE TOOLS TOOL NO. 20 FOLDER 20, TABLE 138 OF STANDARD 1/4" SIZE	3/16	1/16		45	80	12.00	

TABLE 81 PRESSURE ON TOOL IN CUTTING STEEL FORGINGS AND CASTINGS

Table showing that no direct proportion exists: Between the cutting speed and the pressure on the tool
Between the cutting speed and the crushing or tensile strength of the
Between the pressure on the tool and the crushing or tensile strength

The most important data will be found in the five columns with heavy faced type

See paragraphs 502 to 515

WHERE EXPERIMENTS WERE MADE	KIND OF MATERIAL CUT BY THE TOOL	KIND OF TOOLS USED	AIMED AT		ACTUAL SECTIONAL AREA OF CHIP IN SQUARE INCHES	CUTTING SPEED IN FEET PER MINUTE USING STANDARD ROUND NOSED TOOL WITH 3/16" DEPTH OF CUT AND 1/16" FEED	PRESSURE OF CHIP ON TOOL IN TONS (2000 LBS.) PER SQ. INCH SECTIONAL AREA OF CUT	PHYSICAL TESTS OF THE METAL MENTED UPON	
			DEPTH OF CUT IN INCHES	FEED IN INS.				TENSILE STRENGTH IN TONS (2000 LBS) PER SQUARE INCH	PERC ST
MANCHESTER, ENG. IN 1903 See paragraph 000	SOFT STEEL FORGING	MISCELLANEOUS MORERN ENGLISH HIGH SPEED CHROMIUM-TUNGSTEN OR MOLYBDENUM TOOLS HEATED TO MELTING POINT	3/16	1/16		111	128	30	
	MEDIUM STEEL FORGING		3/16	1/16		80	121	32	
	HARD STEEL FORGING		3/16	1/16		41	168	52	
WM. SELLERS & CO. PHILADELPHIA, PA. IN 1902	MEDIUM STEEL (ANNEALED) FORGING	HIGH SPEED CHROMIUM-TUNGSTEN TOOL HEATED TO MELTING POINT	3/16	1/16		64	138	35	
WM. SELLERS & CO. PHILADELPHIA, PA. IN 1883 See paragraph 499	HARD STEEL ROLL	Carbon tempered tools were used in these experiments, but the cutting speeds given are those corresponding to modern high speed Chromium-Tungsten Steels heated to melting point and using a depth of cut of 3/16" and feed 1/16" of quality of tool No. 20 Folder 20, Table 138, of standard 1/4" size.	1 straight edge tool	0.05	0.05	35	128	51	
	STEEL FORGING		2 3/16 straight edge tool	0.02	0.0512	45	132	43	
	HARD STEEL CAR WHEEL CASTING					22	92	48*	

*Estimated

Diagram of Cutting Force on Soft Steel. Expt. No. 636
Feb. 1, 1904. Speed 1 foot in 4½ hours. ⅜ in. Cut.
¼ in. traverse. Tool Angles 60° cutting, 45° plan.

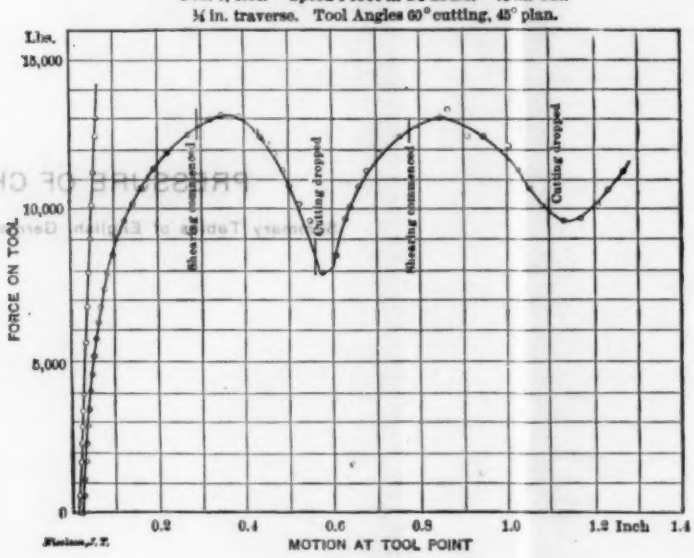


FIG. 82

DIAGRAM SHOWING THE VARIATIONS IN THE PRESSURE OF THE CHIP ON THE TOOL AS THE CHIP IS CUT OR TORN AWAY FROM THE FORGING

Dr. Nicolson's experiments. The tool in this case was cutting at the extraordinarily slow speed of 1 foot in 5 hours and pressure observations were recorded every six one-hundredths (00.0625) of an inch of the cut. (See paragraphs 315 to 324)

Variation of Cutting Forces as Cut progresses. Speed, Dead Sl
Soft Steel (fluid pressed). ⅜ in. cut. ⅛ in. traverse.
Tool Angles 55° cutting, 67½° plan.

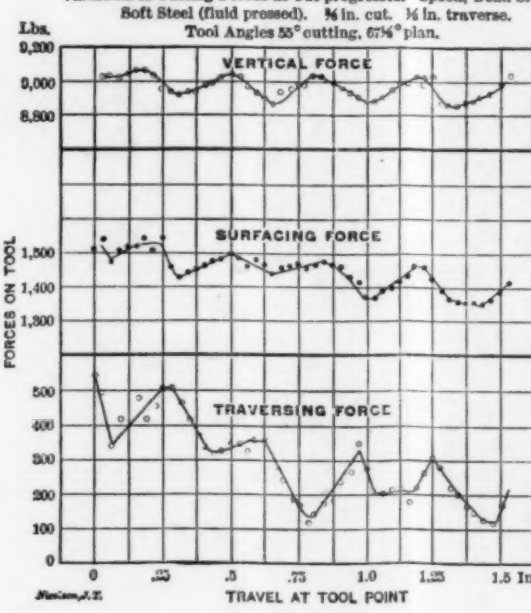


FIG. 86

Dr. Nicolson's experiments: Diagram showing the variation in pressure of the chip on the tool as well as the outward pressure (force") and the feeding pressure (or "traversing force") as the chip away from the forging. The tool in this case was cutting at the ex slow speed of 1 foot in 5 hours and pressure observations were recor one hundredths (00.0625) of an inch of the cut. (See paragraphs 31

ol
Strength of the Cast Iron
ngth
ts, see Folder 5, Figs. 23 and 24

TED	CHEMICAL COMPOSITION OF METALS EXPERIMENTED UPON				
SHING ENGTH NS (2000 ER SQ. IN.	TOTAL CARBON	COMBINED CARBON	GRAPHITE	SILICON	MANGANESE
30	3.062	0.459	2.603	3.010	1.180
49	3.305	0.585	2.720	1.703	0.588
47	3.025	1.150	1.875	1.789	0.348
				1.91	
				1.91	
				1.19	

ngth of the steel
strength

THE METALS EXPERIMENTED UPON		CHEMICAL COMPOSITION OF METALS EXPERIMENTED UPON		
TH S) H	PERCENTAGE OF STRETCH	TOTAL CARBON	SILICON	MANGANESE
	29	0.20	0.055	0.605
	26	0.28	0.086	0.650
	14	0.51	0.111	0.792
	30	0.34	0.183	0.600
	8	0.55		
	14	0.75		
	3*	0.82		

peed, Dead Slow.
n. traverse.
n.

variation in the vertical
pressure (or "surfacing
as the chip is cut or torn
ng at the extraordinarily
were recorded every six
ragraphs 315 to 324)

Pressure of the Chip on the Tool in Cutting Steel and Cast Iron

See paragraphs 480 to 575

Table 83 gives a summary of the pressure of the chip on the tool

Tables 80 and 81 show that no definite relation exists between the pressure of chip on tool and cutting speed pressure of chip on tool and tensile strength of metals being cut

Cutting speed and crushing or tensile strength of metals being cut

For table and diagrams, giving details of experiments on pressure of chip on tool in cutting steel, see Folder 14

For table and diagrams, giving details of experiments on pressure of chip on tool in cutting cast iron, see Folder 13

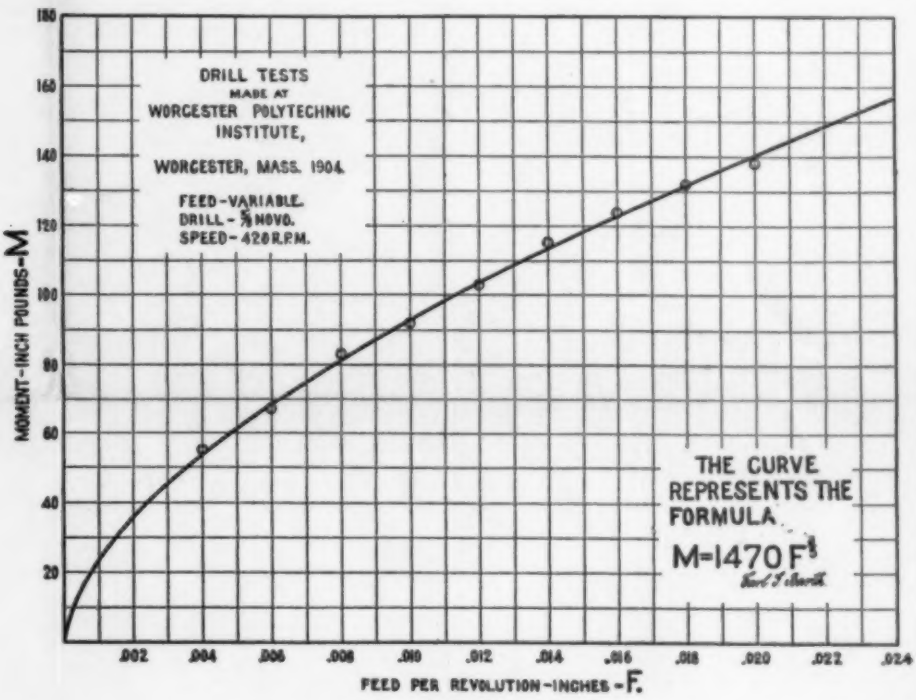


FIG. 85

DRILLING EXPERIMENTS

These experiments were made upon soft cast iron by Profs. W. W. Bird and H. T. Fairfield.

The results of these experiments corroborate the results of our experiments on the Pressure of the Chip upon the Tool in turning Cast Iron, showing that the pressure per square inch of sectional area of the chip becomes greater as the chip becomes thinner. (See Folder 13, Table 92, and paragraphs 555 and 549 to 554)

TABLE 83 SUMMARY OF PRESSURE OF CHIP ON TOOL AND OF FEEDING PRESSURE, ETC. ENGLISH, GERMAN AND AMERICAN EXPERIMENTS

See paragraphs 491 to 496

WHERE EXPERIMENTS WERE MADE	PRESSURE OF CHIP ON TOOL IN TONS (2000 LBS.) PER SQUARE INCH OF SECTION OF CHIP IN CUTTING			PRESSURE REQUIRED TO FEED THE TOOL CUTTING STEEL	PRESSURE OUTWARD, FORCING TOOL HORIZONTALLY AWAY FROM THE WORK	EFFECT OF CUTTING SPEED UPON PRESSURE OF CHIP ON TOOL
	CAST IRON	WROUGHT IRON	STEEL	PER CENT	PER CENT	
MANCHESTER, ENG. BY DR. NICOLSON	53 to 94		121 to 168	0 % to 20 %* of pressure of chip on tool	18% to 78% of pressure of chip on tool	Pressure on tool diminishes slightly as speed increases
GERMAN EXPERIMENTS SUMMARIZED BY MR. HERMAN FISCHER	50 to 85	78 to 120	113 to 170	Equal to pressure of chip on tool		
AMERICAN EXPERIMENTS MADE BY THOSE CONDUCTING THE EXPERIMENTS DESCRIBED IN THIS PAPER	35 to 99		120 to 148	Equal to pressure of chip on tool		No appreciable difference noted in extensive series of experiments when speed was doubled; but machine cuts taken at high speeds consume less power per pound of metal removed than at slow speed, owing to the diminution of friction

*Designers of machine tools are warned not to use this figure in designing gearing, etc., for feeding the tool (See paragraph 496)

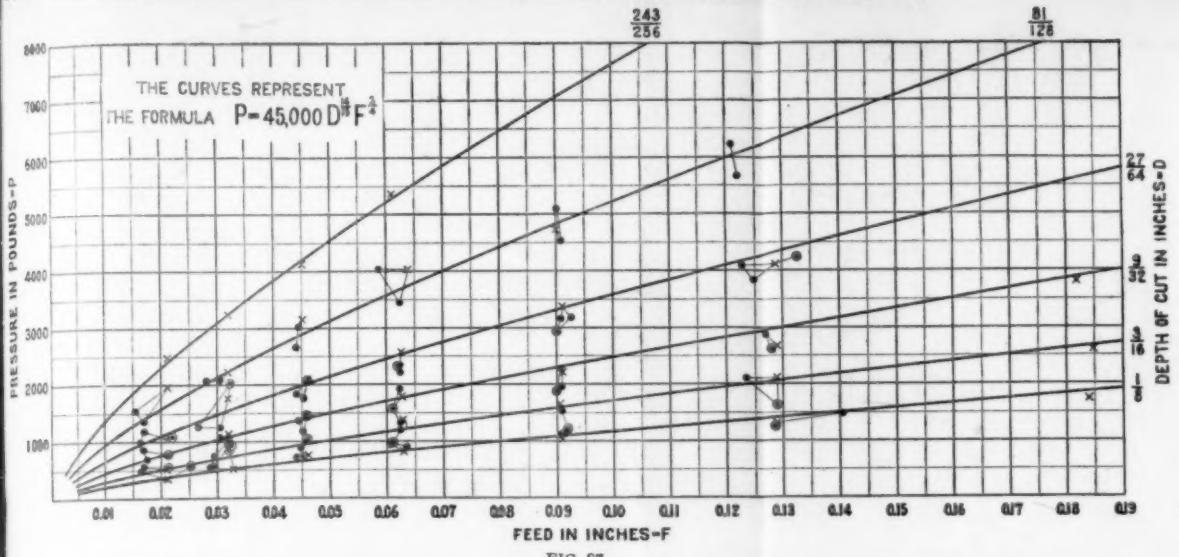


FIG. 87

Summary of experiments on the **Pressure of the Chip on the Tool in cutting Soft Cast Iron** with our Standard ½", ¾" and 1¼" Round Nose Roughing Tools, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5 and Figs. 21a, 25d, 25b, with various Feeds and Depths of Cut. Cutting Speed about 60′ per minute.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of the chip, see Folder 13, Table 92. On diagrams 89, 88 and 90 will be found the plotted pressures recorded for each of the three sizes of tools.

⊙ = ½" tool
● = ¾" tool
× = 1¼" tool

SILICON, 1.7 PER CENT — TENSILE STRENGTH, 1240 LBS.

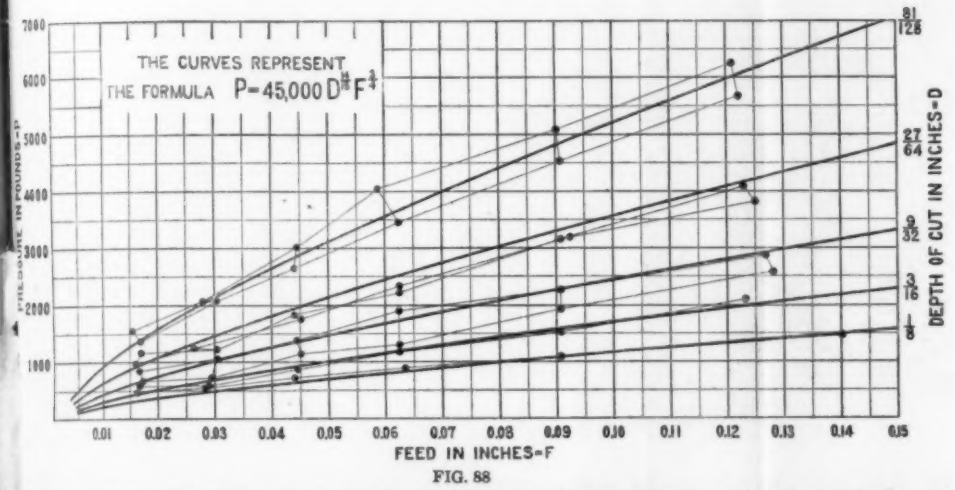


FIG. 88

Details of experiments on the **Pressure of the Chip on the Tool in cutting Soft Cast Iron** with our Standard ¾" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slop 14°, shown in Folder 5, Fig. 25b, with various Feeds and Depths of Cutting Speed about 60′ per minute.

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

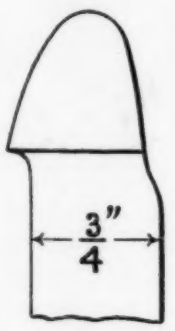
See paragraphs 535 to 565.

The pressures given in this diagram will be found combined with those obtained while using ½" and 1¼" tools at the same cutting speed, in cutting metal of the same quality, in Folder 13, Fig. 87. Note that the same curves and formula fit tools of different sizes fairly well.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of the chip, see Folder 13, Table 92.

For the chemical composition and physical tests of the Cast Iron experimented upon, see Folder 13, Fig. 92.

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°



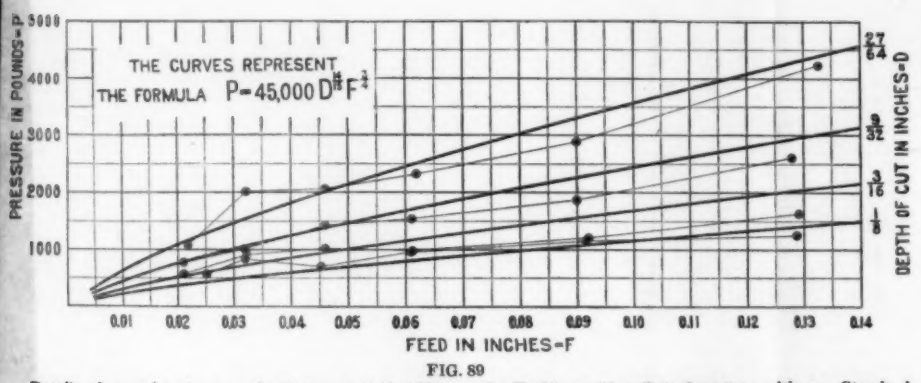


FIG. 89

Details of experiments upon the **Pressure of the Chip on the Tool in cutting Soft Cast Iron** with our Standard ½" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25d, with various Feeds and Depths of Cut. Cutting speed about 60′ per minute.

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

See paragraphs 535 to 565.

The pressures given in this diagram will be found combined with those obtained while using ¾" and 1¼" tools at the same cutting speed, in cutting metal of the same quality in Folder 13, Fig. 87. Note that the same curves and formula fit tools of different sizes fairly well.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of the chip, see Folder 13, Table 87.

For the chemical composition and physical tests of the Cast Iron experimented upon, see Folder 13, Fig. 87.

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°

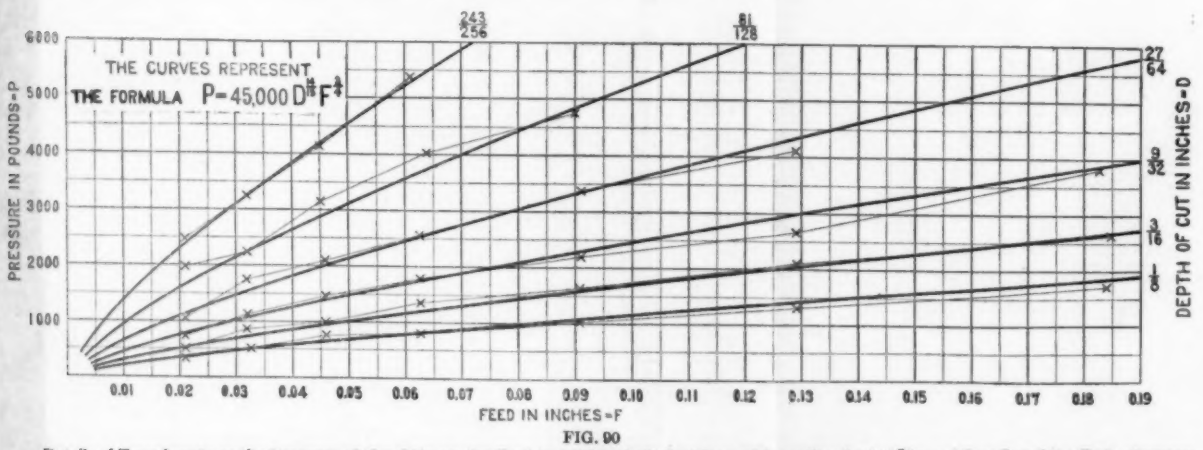


FIG. 90

Details of Experiments on the **Pressure of the Chip on the Tool in cutting Soft Cast Iron** with our Standard 1¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, with various Feeds and Depths of cut. Cutting Speed about 60′ per minute

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

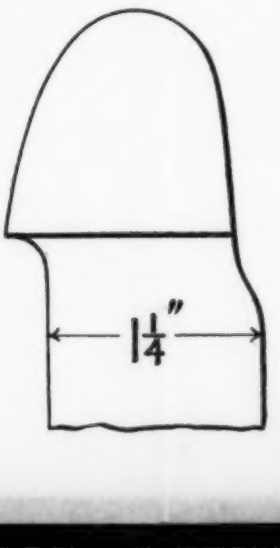
See paragraphs 535 to 565.

The pressures given in this diagram will be found combined with those obtained while using ½" and ¾" tools at the same cutting speed, in cutting metal of the same quality, in Folder 13, Fig. 87. Note that the same curves and formula fit tools of different sizes fairly well.

For the exact pressure recorded in these experiments and their equivalents in pounds per square inch of sectional area of the chip, see Folder 13, Table 92.

For the chemical composition and physical tests of the Cast Iron experimented upon, see Folder 13, Fig. 92.

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°



With

TENSILE STRENGTH, 124

½" TOOL

SEE FOLDER 13, FIG. 89

DEPTH OF CUT IN INCHES	EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE I ON TOOL	P
1/8	930	0.0252	592	
	931	0.0320	854	
	932	0.0452	723	
	933	0.0608	970	
	934	0.0916	1167	
	935	0.1288	1266	
3/16	936	0.0212	576	
	937	0.0324	914	
	938	0.0460	1016	
	939	0.0612	983	
	940	0.0920	1202	
	941	0.1292	1642	
9/32	942	0.0212	793	
	943	0.0320	1008	
	944	0.0460	1405	
	945	0.0612	1570	
	946	0.0900	1883	
	947	0.1280	2628	
27/64	948	0.0220	1088	
	949	0.0324	2012	
	950	0.0460	2068	
	951	0.0620	2321	
	952	0.0900	2940	
	953	0.1327	4240	
81/128				
243/256				

Details of ex
angle 6°, back s
Place and D
See paragrap
For the exac
Note that the
69,000 for Hard

TABLE 92 THE PRESSURES OF THE CHIP ON THE TOOL IN CUTTING CAST IRON

With our Standard Round Nose Roughing Tools, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Figs. 21a, 25d, 25b, 25e, with various Fee

For diagram of these experiments, see Folder 13, Fig. 87. See paragraphs 535 to 565

SOFT CAST IRON

ENGTH, 12400

CHEMICAL COMPOSITION
Combined Carbon
Graphite
Manganese
Silicon, 1.7 per cent
Phosphorus
Sulphur

Tensile St
Silicon. . .

OOL R 13, FIG. 89		3/4" TOOL SEE FOLDER 13, FIG. 88				3/4" TOOL SEE FOLDER 13, FIG. 88				1 1/4" TOOL SEE FOLDER 13, FIG. 90					
PRESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS		EXPERIMENT NUMBER	
ON TOOL	PER SQ. IN.			ON TOOL	PER SQ. IN			ON TOOL	PER SQ. IN.			ON TOOL	PER SQ. IN		
592	188000	483	0.0164	475	232000					954	0.0212	337	127000		
854	213000	484	0.0286	552	154000					955	0.0328	526	128000		
723	128000	485	0.0440	721	141000					956	0.0460	772	134000		
970	127000	486	0.0635	905	114000					957	0.0628	805	102000	1153	
1167	102000	487	0.0900	1115	99000					958	0.0908	1019	90000	1154	
1266	79000	488	0.1403	1490	88000					959	0.1292	1315	81000	1155	
										960	0.1840	1740	77000	1156	
576	145000	489	0.0168	581	184000					961	0.0212	525	132000		
914	150000	490	0.0292	581	106000					962	0.0320	881	147000		
1016	118000	491	0.0446	888	106000					963	0.0460	1000	114000	1157	
983	86000	492	0.0625	1195	102000					964	0.0628	1355	115000	1158	
1202	69000	493	0.0900	1533	90000					965	0.0908	1643	96000	1159	
1642	67000	494	0.1234	2100	93000					966	0.1292	2115	90000	1160	
										967	0.1848	2618	75000	1161	
793	132000	512	0.0174	684	139000	469	0.0168	861	182000	968	0.0212	751	126000		
1008	112000	511	0.0294	735	88000	470	0.0304	1092	128000	969	0.0320	1135	126000	1162	
1405	108000	510	0.0452	1163	91000	471	0.0444	1360	109000	970	0.0460	1467	113000	1163	
1570	93000	509	0.0625	1317	74000	472	0.0625	1922	109000	971	0.0628	1785	92000	1164	
1883	74000	508	0.0909	1949	76000	473	0.0909	2272	89000	972	0.0912	2205	86000	1165	
2628	72000	507	0.1282	2600	72000	474	0.1270	2870	80000	973	0.1292	2670	82000	1166	
										974	0.1828	3810	74000	1167	
1088	117000	501	0.0162	998	146000	463	0.0171	1174	162000	975	0.0212	1052	114000	1168	
2012	149000	502	0.0264	1260	113000	464	0.0304	1245	97000	976	0.0320	1757	120000	1169	
2068	107000	503	0.0452	1770	92000	465	0.0440	1837	99000	977	0.0460	2088	107000	1170	
2321	88000	504	0.0625	2345	88000	466	0.0625	2220	84000	978	0.0628	2568	91000	1171	
2940	77000	505	0.0926	3200	82000	467	0.0909	3169	83000	979	0.0912	3373	87000	1172	
4240	73000	506	0.1250	3830	72000	468	0.1231	4082	78000	980	0.1292	4108	75000	1173	
		500	0.0156	1556	157000	457	0.0170	1365	126000	981	0.0212	1984	142000	1174	
		499	0.0280	2090	117000	458	0.0304	2088	157000	982	0.0320	2245	111000	1175	
		498	0.0446	3020	107000	459	0.0440	2663	96000	983	0.0452	3164	110000	1176	
		496	0.0588	4040	109000	460	0.0625	3450	87000	984	0.0640	4022	99000	1177	
		497	0.0901	5095	89000	461	0.0900	4525	78000	985	0.0900	4744	83000	1178	
		495	0.1212	6240	81000	462	0.1222	5685	73000						
										986	0.0212	2482	123000		
										987	0.0320	3260	107000		
										988	0.0452	4140	96000		
										989	0.0612	5370	92000		

Place and Date of Experiments: WM. SELLERS & CO., INC., PHILADELPHIA, PA., 1902

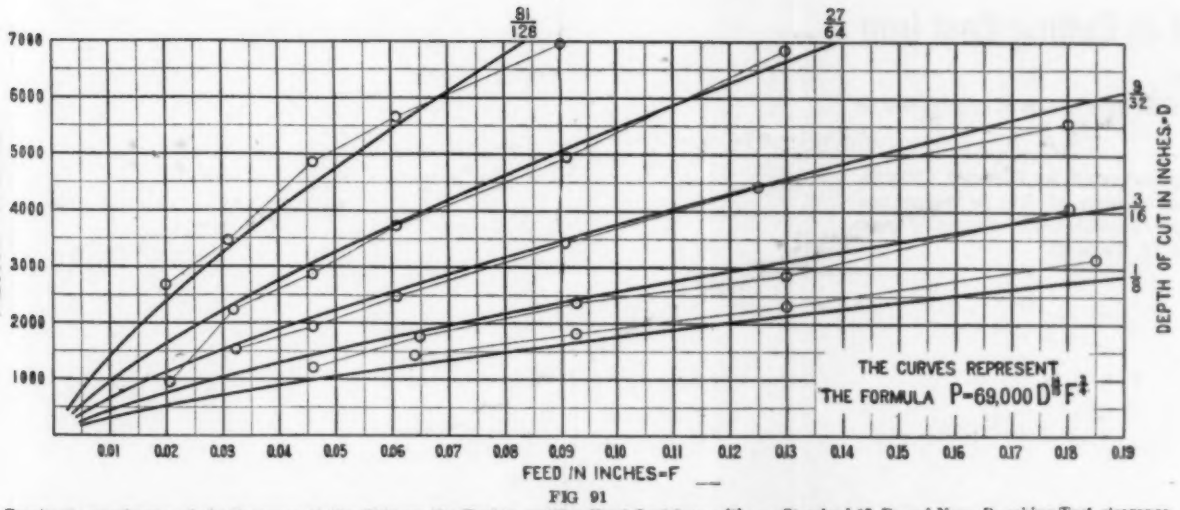


FIG 91

Details of experiments of the **Pressure of the Chip on the Tool in cutting Hard Cast Iron** with our Standard 1" Round Nose Roughing Tool, clearance gle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25a, with various Feeds and Depths of cut. Cutting Speed about 60′ per minute.
Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.
See paragraphs 535 to 565.
For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of chip, see Folder 13, Table 92.
Note that the formula for the pressure in cutting Hard Cast Iron is the same as that for cutting Soft Cast Iron except for the coefficients which are equal to ,000 for Hard and 45,000 for Soft. See Folder 13 and Figs. 88, 89 and 98.

SILICON, 1.2 PER CENT — TENSILE STRENGTH, 24000 LBS

TABLE 92 THE PRESSURES OF THE CHIP ON THE TOOL IN CUTTING

With our Standard Round Nose Roughing Tools, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Figs. 21a, 25d, 25b, 25e,

For diagram of these experiments, see Folder 13, Fig. 87. See paragraphs 535 to

SOFT CAST IRON

NGTH, 12400

CHEMICAL COMPOSITION
Combined Carbon
Graphite
Manganese
Silicon, 1.7 per cent
Phosphorus
Sulphur

OL 13, FIG. 89		3/4" TOOL SEE FOLDER 13, FIG. 88				3/4" TOOL SEE FOLDER 13, FIG. 88				1 1/4" TOOL. SEE FOLDER 13, FIG. 90			
RESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN	
N TOOL	PER SQ. IN.			ON TOOL	PER SQ. IN			ON TOOL	PER SQ. IN.			ON TOOL	PER
592	188000	483	0.0164	475	23200					954	0.0212	337	12
854	213000	484	0.0286	552	15400					955	0.0328	526	12
723	128000	485	0.0440	721	14100					956	0.0460	772	13
970	127000	486	0.0635	905	11400					957	0.0628	805	10
1167	102000	487	0.0900	1115	9900					958	0.0908	1019	9
1266	79000	488	0.1403	1490	8800					959	0.1292	1315	8
										960	0.1840	1740	7
576	145000	489	0.0168	581	18400					961	0.0212	525	13
914	150000	490	0.0292	581	10600					962	0.0320	881	14
1016	118000	491	0.0446	888	10600					963	0.0460	1000	11
983	86000	492	0.0625	1195	10200					964	0.0628	1355	11
1202	69000	493	0.0900	1533	9000					965	0.0908	1643	9
1642	67000	494	0.1234	2100	9300					966	0.1292	2115	9
										967	0.1848	2618	7
793	132000	512	0.0174	684	13900	469	0.0168	861	182000	968	0.0212	751	13
1008	112000	511	0.0294	735	8800	470	0.0304	1092	128000	969	0.0320	1135	12
1405	108000	510	0.0452	1163	9100	471	0.0444	1360	109000	970	0.0460	1467	11
1570	93000	509	0.0625	1317	7400	472	0.0625	1922	109000	971	0.0628	1785	9
1883	74000	508	0.0909	1949	7600	473	0.0909	2272	89000	972	0.0912	2205	8
2628	72000	507	0.1282	2600	7200	474	0.1270	2870	80000	973	0.1292	2670	8
										974	0.1828	3810	7
1088	117000	501	0.0162	998	14600	463	0.0171	1174	162000	975	0.0212	1052	14
2012	149000	502	0.0264	1260	11300	464	0.0304	1245	97000	976	0.0320	1757	15
2068	107000	503	0.0452	1770	9200	465	0.0440	1837	99000	977	0.0460	2088	14
2321	88000	504	0.0625	2345	8800	466	0.0625	2220	84000	978	0.0628	2568	11
2940	77000	505	0.0926	3200	8200	467	0.0909	3169	83000	979	0.0912	3373	11
4240	73000	506	0.1250	3830	7200	468	0.1231	4082	78000	980	0.1292	4108	11
		500	0.0156	1556	15700	457	0.0170	1365	126000	981	0.0212	1984	18
		499	0.0280	2090	11700	458	0.0304	2088	157000	982	0.0320	2245	16
		498	0.0446	3020	10700	459	0.0440	2663	96000	983	0.0452	3164	14
		496	0.0588	4040	10900	460	0.0625	3450	87000	984	0.0640	4022	12
		497	0.0901	5095	8900	461	0.0909	4525	78000	985	0.0900	4744	10
		495	0.1212	6240	8100	462	0.1222	5685	73000				
										986	0.0212	2482	18
										987	0.0320	3260	16
										988	0.0452	4140	14
										989	0.0612	5370	11

Place and Date of Experiments: WM. SELLERS & CO., INC., PHILADELP

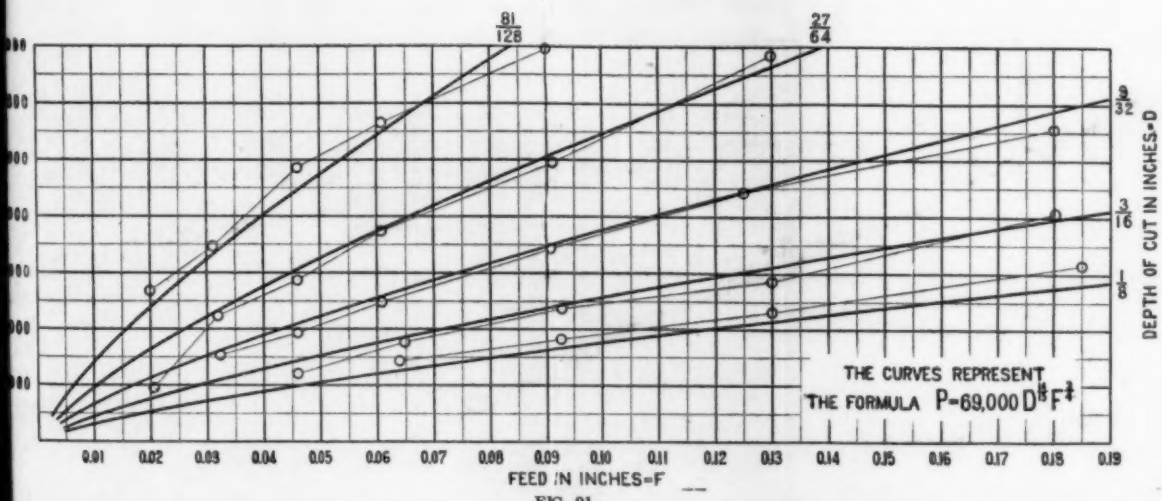


FIG 91

ails of experiments of the **Pressure of the Chip on the Tool in cutting Hard Cast Iron** with our Standard 1" Round Nose Roughing Tool, clearance 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25a, with various Feeds and Depths of cut. Cutting Speed about 60' per minute.
ce and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.
paragraphs 535 to 565.
the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of chip, see Folder 13, Table 92.
te that the formula for the pressure in cutting Hard Cast Iron is the same as that for cutting Soft Cast Iron except for the coefficients which are equal to for Hard and 45,000 for Soft. See Folder 13 and Figs. 88, 89 and 98.

SILICON, 1.2 PER CENT TENSILE STRENGTH, 24000 LBS

N CUTTING CAST IRON

5d, 25b, 25e, with various Feeds and Depths of Cut. Cutting Speed about 60′ per minute

agraphs 535 to 565

HARD CAST IRON

Tensile Strength 24000
Silicon..... 1.2 per cent

PRESSURE IN POUNDS IN CUTTING SOFT CAST IRON FIGURED BY FORMULA

$45{,}000\ D^{\frac{1}{2}}\ F^{\frac{1}{2}}$

COMPARE THESE PRESSURES WITH THE EXPERIMENTAL PRESSURES IN THE FIRST FOUR COLUMNS OF THIS TABLE

PRESSURE IN POUNDS IN CUTTING HARD CAST IRON FIGURED BY FORMULA

$69{,}000\ D^{\frac{1}{2}}\ F^{\frac{1}{2}}$

COMPARE THESE PRESSURES WITH THE EXPERIMENTAL PRESSURES IN THE FIFTH COLUMN OF THIS TABLE

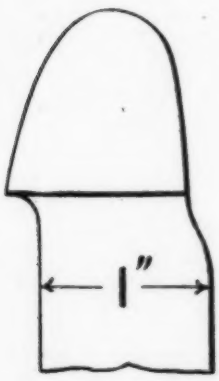
OOL.
3, FIG. 90

1″ TOOL
SEE FOLDER 13, FIG. 91

RESSURE IN POUNDS		EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS		FEED IN		PRESSURE IN POUNDS		PRESSURE IN POUNDS	
N TOOL	PER SQ. IN			ON TOOL	PER SQ. IN.	FRACTIONS	DECIMALS	ON TOOL	PER SQ. IN.	ON TOOL	PER SQ. IN.
337	127000					1/64	0.01562	289	146206	438	224182
526	128000					1/32	0.03125	480	122899	736	188445
772	134000					3/64	0.04687	651	111092	1000	170342
805	102000	1153	0.0640	1430	178000	1/16	0.06250	808	103383	1238	158521
1019	90000	1154	0.0928	1820	157000	3/32	0.09375	1168	93419	1679	143313
1315	81000	1155	0.1300	2325	135000	1/8	0.12500	1358	86930	2083	133292
1740	77000	1156	0.1850	3166	140000	3/16	0.18750	1764	78604	2825	120526
525	132000					1/64	0.01562	417	142379	640	218314
881	147000					1/32	0.03125	701	119683	1075	183515
1000	114000	1157	0.0460	1220	141000	3/64	0.04687	951	108184	1458	165889
1355	115000	1158	0.0648	1775	145000	1/16	0.06250	1180	100677	1809	154371
1643	96000	1159	0.0928	2360	135000	3/32	0.09375	1599	90974	2452	139494
2115	90000	1160	0.1300	2860	117000	1/8	0.12500	1984	84648	3042	129803
2618	75000	1161	0.1815	4070	119000	3/16	0.18750	2690	76503	4124	117304
751	126000					1/64	0.01562	609	138511	933	212384
1135	126000	1162	0.0324	1545	169000	1/32	0.03125	1024	116474	1543	175593
1467	113000	1163	0.0460	1925	148000	3/64	0.04687	1364	105266	2127	161377
1785	92000	1164	0.0608	2478	144000	1/16	0.06250	1722	97942	2640	150178
2205	86000	1165	0.0908	3440	134000	3/32	0.09375	2334	88502	3577	135673
2670	82000	1166	0.1250	4485	127000	1/8	0.12500	2893	82294	4437	126215
3810	74000	1167	0.1800	5570	110000	3/16	0.18750	3933	74474	5045	141 93
1052	114000	1168	0.0204	986	114000	1/64	0.01562	889	134817	1363	206720
1757	120000	1169	0.0320	2250	166000	1/32	0.03125	1495	113368	2292	173830
2088	107000	1170	0.0460	2880	148000	3/64	0.04687	2026	102439	3106	157073
2568	91000	1171	0.0608	3740	145000	1/16	0.06250	2514	95330	3854	146173
3373	87000	1172	0.0912	4960	128000	3/32	0.09375	3453	86143	5225	132085
4108	75000	1173	0.1288	6850	126000	1/8	0.12500	4227	80158	6481	122910
1984	142000	1174	0.0200	2688	212000	1/64	0.01562	1297	131222	1994	201207
2245	111000	1175	0.0312	3490	177000	1/32	0.03125	2183	110344	3346	169194
3164	110000	1176	0.0460	4865	167000	3/64	0.04687	2958	99707	4535	152884
4022	99000	1177	0.0608	5660	145000	1/16	0.06250	3670	92788	5627	142274
4744	83000	1178	0.0900	6960	122000	3/32	0.09375	4974	83845	7627	128563
						1/8	0.12500	6172	78025	9700	122638
2482	123000					1/64	0.01562	1894	127722	2121	195841
3260	107000					1/32	0.03125	3189	107437	3568	164736
4140	96000					3/64	0.04687	4437	97052	4847	148814
5370	92000					1/16	0.06250	5358	90313	6013	138480

, PHILADELPHIA, PA., 1902

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°



Pressure of the Chip on the Tool in Cutting Cast Iron

See paragraphs 535 to 565

Table 92 and Diagrams 87, 88, 89, 90, 91 on this folder all give details of experiments on pressure of chip on the tool while cutting cast iron.

For corresponding experiments on steel, see Folder 14.

For summary table of pressure of chip on tool cutting various metals, see Folder 12, Table 83.

For table showing lack of any definite relation between pressure of chip on the tool and cutting speed; pressure of chips on tool and tensile strength of metals being cut; cutting speed and crushing or tensile strength of metals cut, see Folder 12, Table 80.

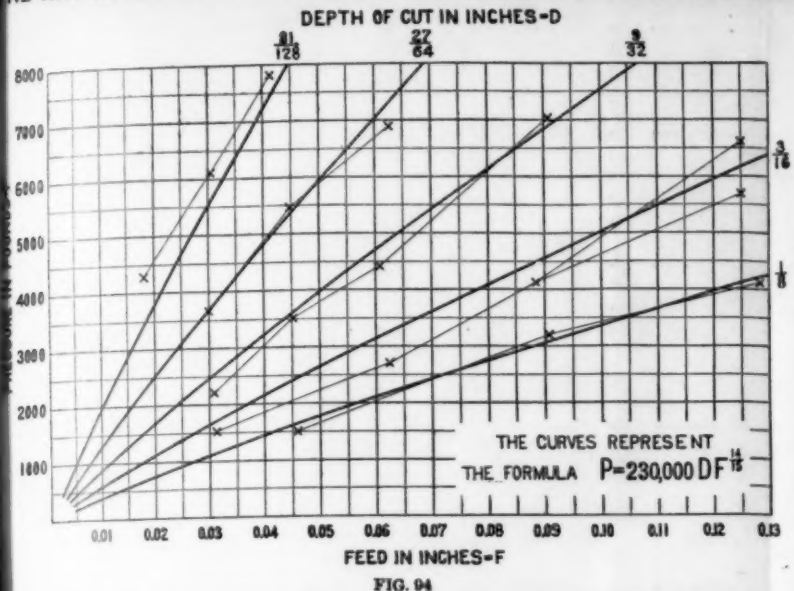


FIG. 94

Details of experiments upon the **Pressure of the Chip on the Tool in Cutting Steel** with our Standard ¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25b, with various Feeds and Depths of Cut. Cutting speed about 30 feet per minute

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

See paragraphs 566 to 577.

The pressures given on this diagram will be found combined with those obtained while using ¼" tools at 60′ cutting speed ½" tools at 60′ cutting speed, and 1½" tools at 30′ cutting speed, in cutting metal of the same quality, in Folder 14, Fig. 98. Note that the same curve and formula fit tools of different sizes fairly well.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of the chip, see Folder 14, Table 99.

For the chemical composition and physical tests of the steel experimented upon, see Folder 14, Fig. 98.

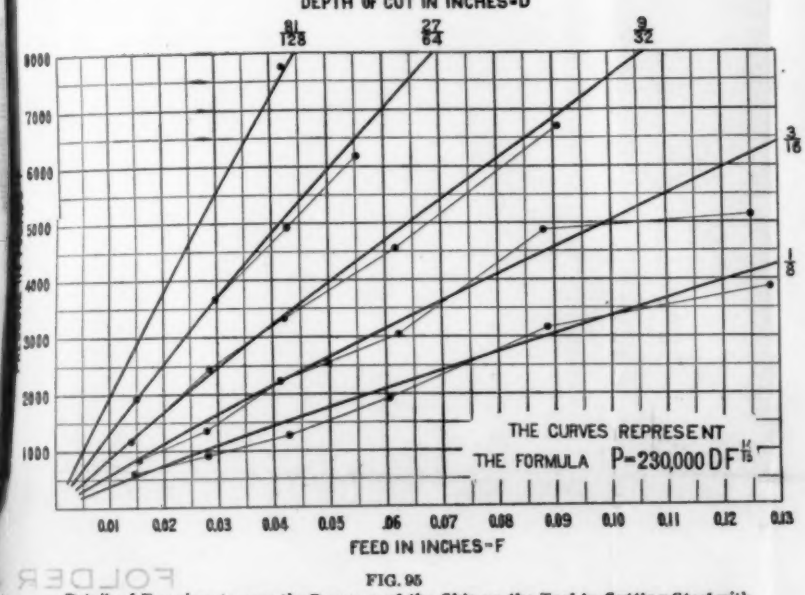


FIG. 95

Details of Experiments upon the **Pressure of the Chip on the Tool in Cutting Steel** with our ¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25b, with various Feeds and Depths of Cut. Cutting Speed about 60′ per minute.

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

See paragraphs 566 to 577.

The pressures given on this diagram will be found combined with those obtained while using ¼" tools at 60′ cutting speed, ½" tools at 30′ cutting speed and 1½" tools at 30′ cutting speed, in cutting metal of the same quality, in Folder 14, Fig. 98. Note that the same curves and formula fit tools of different sizes fairly well.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of the chip, see Folder 14, Table 99.

For the chemical composition and the physical tests of the steel experimented upon, see Folder 14, Fig. 98.

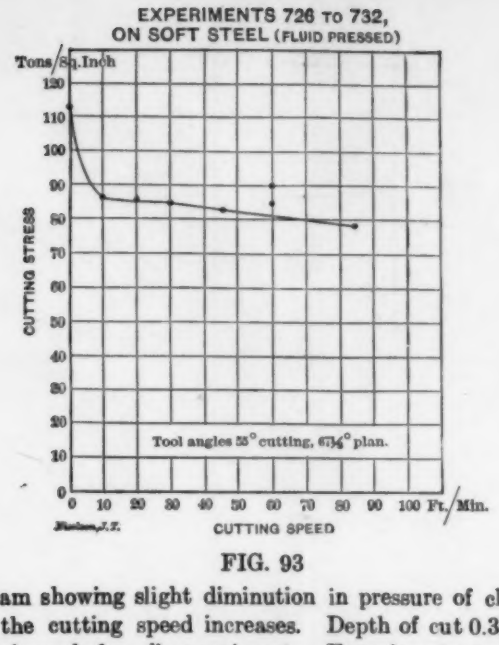
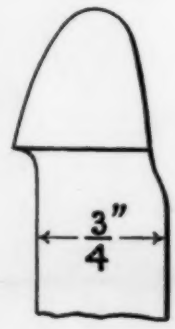


FIG. 93

Diagram showing slight diminution in pressure of ch
tool as the cutting speed increases. Depth of cut 0.35
Same tool used for all experiments. Experiments mad
Nicolson. (See paragraph 578)



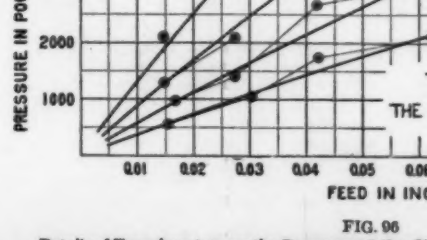


FIG. 96

Details of Experiments upon the **Pressure of the Ch**
our Standard ¼" Round Nose Roughing Tool, clearance
shown in Folder 5, Fig. 25d, with various Feeds and D
per minute.

Place and Date of Experiments: Wm. Sellers & Co.,

See paragraphs 566 to 577.

The pressures given on this diagram will be found c
¼" tools at 30′ cutting speed, ½" tools at 60′ cutting speed
metal of the same quality in Folder 14, Fig. 98. Note t
of different sizes fairly well.

For the exact pressures recorded in these experime
square inch of sectional area of chip, see Folder 14, Tab

For the chemical composition and physical tests of
14, Fig. 98.

TABLE 99 THE PRESSURE OF THE CHIP ON THE TOOL IN CUTTING STEEL WITH OUR STANDARD ROUND NOSE R

Clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Figs. 21a, 25d, 25b and 25e, with various Feeds and Dept

See paragraphs 566 to 577; see Folder 13, Figs. 94, 95, 96 and 97

	¼" TOOL CUTTING SPEED ABOUT 60′ PER MINUTE SEE FOLDER 13, FIG. 96				½" TOOL CUTTING SPEED ABOUT 30′ PER MINUTE SEE FOLDER 13, FIG. 94				¾" TOOL CUTTING SPEED ABOUT 60′ PER MINUTE SEE FOLDER 13, FIG. 95				1½" TOOL CUTTING SPEED ABOUT 30′ PER M SEE FOLDER 13, FIG. 97			
DEPTH OF CUT IN INCHES	EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS ON TOOL	PRESSURE IN POUNDS PER SQ. IN.	EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS ON TOOL	PRESSURE IN POUNDS PER SQ. IN.	EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE IN POUNDS ON TOOL	PRESSURE IN POUNDS PER SQ. IN.	EXPERIMENT NUMBER	FEED IN INCHES	PRESSURE I ON TOOL	P
1/8	565	0.0154	586	304000					435	0.0144	605	336000	541	0.0186	709	
	566	0.0305	1040	273000					434	0.0281	907	258000	542	0.0296	1124	
	567	0.0422	1730	328000	535	0.0460	1537	267000	433	0.0428	1286	240000	543	0.0448	1615	
	568	0.0625	2120	271000					432	0.0606	1928	254000	544	0.0608	1930	
	569	0.0909	2850	250000	534	0.0909	3230	284000	431	0.0888	3175	286000	545	0.0930	3230	
					534½	0.1282	4138	256000	430	0.1275	3855	242000	546	0.1250	4510	
3/16	570	0.0166	993	319000					415	0.0115	736	341000	552	0.0156	865	
	571	0.0275	1400	271000	523	0.0314	1542	262000	414	0.0280	1345	256000	551	0.0300	1496	
	572	0.0420	2690	341000					413	0.0414	2238	288000	550	0.0440	1986	
	573	0.0625	3100	265000	520	0.0625	2721	232000	412	0.0625	3020	258000	549	0.0632	2760	
					521	0 0885	4150	250000	416	0 0882	4884	295000	548	0.0909	4600	
					522 539	0.0125	6620 5700	282000 243000	538	0.1250	5160	220000	547	0.1250	6000	
9/32	574	0.0148	1300	342000					429	0.0140	1184	301000	553	0.0148	1230	
	575	0.0275	2100	272000	530	0.0310	2230	255000	428	0.0287	2405	298000	554	0.0286	2135	
					531	0.0452	3520	277000	427	0.0423	3320	278000	555	0.0403	2790	
					532	0.0606	4430	239000	426	0.0620	4680	268000	556	0.0645	4630	
					533	0.0909	7050	275000	425	0.0909	6708	262000	557	0.0909	6680	
27/64	577	0.0148	2130	341000					424	0.0150	1932	305000	558	0.0174	2090	
					529	0.0300	3680	290000	423	0.0298	3665	291000	559	0.0285	3360	
					527	0.0448	5460	238000	422	0.0427	4930	273000	560	0.0405	4640	
					528	0.0625	6920	262000	421	0.0552	6200	266000	561 576	0.0606	5760 6730	
81/128					525	0.0182	4270	371000					562	0.0154	2980	
					524	0.0306	6140	317000					563	0.0282	5760	
					526	0.0415	7815	297000	420	0.0424	7776	289000	564	0.0400	7700	

ssure of chip on the
of cut 0.35", feed $\frac{1}{8}$".
iments made by Dr.

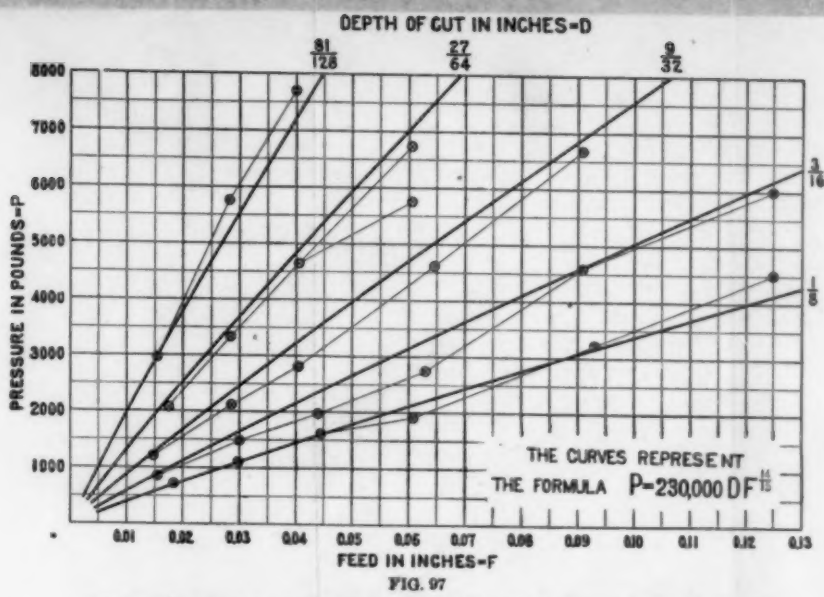


FIG. 97

Details of Experiments upon the Pressure of the Chip on the Tool in Cutting Steel with our Standard 1¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25e, with various Feeds and Depths of Cut. Cutting Speed about 30′ per minute.

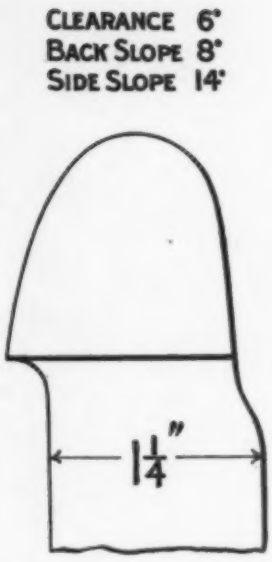
Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

See paragraphs 566 to 577.

The pressures given on this diagram will be found combined with those obtained while using ¼" tools at 60′ cutting speed, ½" tools at 30′ cutting speed, and ¾" tools at 60′ cutting speed, in cutting metal of the same quality in Folder 14, Fig 98. Note that the same curves and formula fit tools of different sizes fairly well.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of chip, see Folder 14, Table 99.

For chemical composition and physical tests of the Steel experimented upon, see Folder 14, Fig. 98.



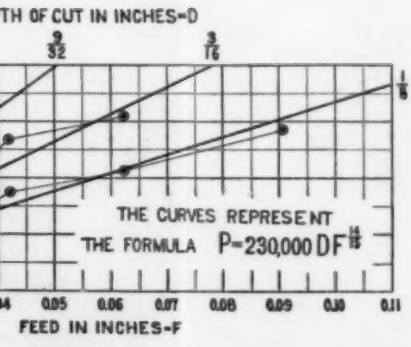


FIG. 96

ssure of the Chip on the Tool in Cutting Steel with
Tool, clearance angle 6°, back slope 8°, side slope 14°,
us Feeds and Depths of Cut. Cutting Speed about 60′

m. Sellers & Co., Inc., Philadelphia, Pa., 1902.

will be found combined with those obtained while using
60′ cutting speed, 1¼" tools at 30′ cutting speed, in cutting
Fig. 98. Note that the same curves and formula fit tools

these experiments and their equivalents in pounds per
e Folder 14, Table 99.
hysical tests of the steel experimented upon, see Folder

Pressure of the Chip on the Tool in Cutting Steel

See paragraphs 566 to 577

Table 99 and diagrams 94, 95, 96, 97 and 98 on this folder all refer to experiments on pressure of chip on the tool while cutting steel. For corresponding experiments upon cast iron, see Folder 13.

For summary table of pressure of chip on tool, cutting various metals, see Folder 12, Table 83.

For tables showing lack of any definite relation between pressure of chip on the tool and cutting speed; pressure of chip on tool and tensile strength of metals being cut; between cutting speed and crushing or tensile strength of metals cut see Folder 12, Tables 80 and 81.

ND NOSE ROUGHING TOOLS

eds and Depths of Cut

" TOOL BOUT 30′ PER MINUTE ER 13, FIG. 97			PRESSURE IN POUNDS, FIGURED BY FORMULA—230,000 $DF^{\frac{11}{16}}$ COMPARE THESE PRESSURES WITH THE EXPERIMENTAL PRESSURES IN THE OTHER FOUR COLUMNS OF THIS TABLE			
	PRESSURE IN POUNDS		FEED IN		PRESSURE IN POUNDS	
	ON TOOL	PER SQ. IN.	FRACTIONS	DECIMALS	ON TOOL	PER SQ. IN.
	709	306000	1/64	0.01562	593	303550
	1124	304000	1/32	0.03125	1132	289842
	1615	288000	3/64	0.04687	1653	282054
	1930	253000	1/16	0.06250	2162	276754
	3230	278000	3/32	0.09375	3156	269314
	4510	288000	1/8	0.12500	4129	264256
	865	295000	1/64	0.01562	889	303550
	1496	266000	1/32	0.03125	1698	289842
	1986	241000	3/64	0.04687	2479	282054
	2760	237000	1/16	0.06250	3243	276754
	4600	270000	3/32	0.09375	4734	269314
	6000	257000	1/8	0.12500	6194	264256
	1230	296000	1/64	0.01562	1334	303550
	2135	265000	1/32	0 03125	2547	289842
	2790	246000	3/64	0 04687	3718	282054
	4630	255000	1/16	0.06250	4865	276754
	6680	248000	3/32	0.09375	7101	269314
	2090	285000	1/64	0.01562	2001	303550
	3360	279000	1/32	0.03125	3821	289842
	4640	271000	3/64	0.04687	5578	282054
	5760 6730	225000 263000	1/16	0.06250	7297	276754
	2980	305000	1/64	0.01562	3001	303550
	5760	327000	1/32	0.03125	5732	289842
	7700	304000	3/64	0.04687	8367	283054

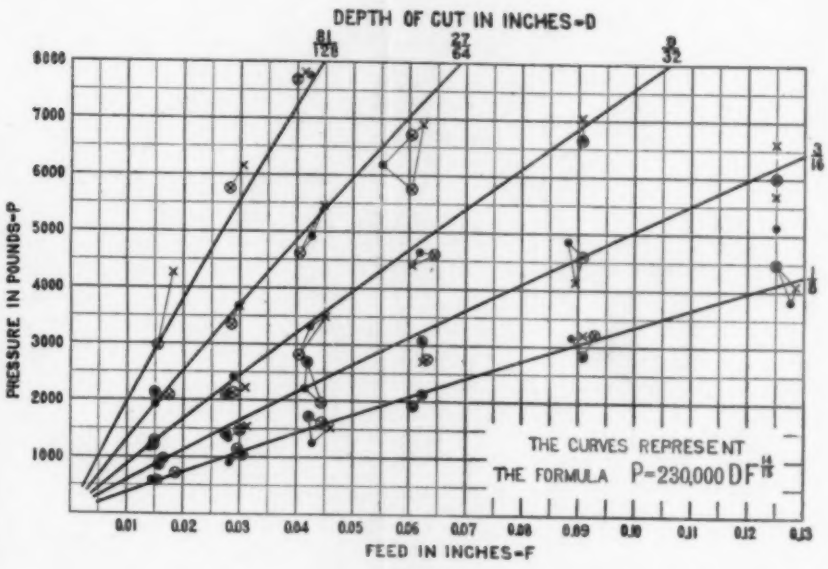


FIG. 98

Summary of Experiments upon the Pressure of the Chip on the Tool in Cutting Steel with our Standard ¼", ½" and 1¼" Round Nose Roughing Tools, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 21a, with various Feeds and Depths of Cut.

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902.

See paragraphs 566 to 577.

For the exact pressures recorded in these experiments and their equivalents in pounds per square inch of sectional area of chip, see Folder 14, Table 99.

On diagrams 94, 95, 96 and 97 will be found the pressures recorded for each of the three sizes of tools.

⊙ = ¼" tool, Cutting Speed 60′ per minute.
● = ½" tool, Cutting Speed 60′ per minute.
× = ½" tool, Cutting Speed 30′ per minute.
⊕ = 1¼" tool, Cutting Speed 30′ per minute.

Note that spots marked ● = 60′ cutting speed and × = 30′ cutting speed with same shaped tool ½" round nose. These experiments show that cutting speed has but little effect upon the pressure of the chip upon the tool.

Chemical Composition		Physical Properties	
Carbon	0.34	Tensile Strength	70280
Manganese	0.54	Elastic Limit	33610
Silicon	0.176	Elongation	23.00
Phosphorus	0 037	Contraction	28.08
Sulphur	0.026	Annealed at 1300°	

TABLE 103 EFFECT ON CUTTING SPEED OF TIME TOOL IS UNDER CUT IN CUTTING STEEL

See paragraphs 262 and 696 to 704

Feed $\frac{1}{16}$" Depth of Cut $\frac{3}{16}$" $\frac{7}{8}$" Standard Round Nose Tool Clearance Angle 6°, Back Slope 8°, Side Slope 14°. See Folder 5, Fig. 24

10 MINUTE RUNS					20 MINUTE RUNS					40 MINUTE RUNS					80 MINUTE RUNS				
EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET	DURATION OF CUT	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET	DURATION OF CUT	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET	DURATION OF CUT	CONDITION OF TOOL	EXPERIMENT NUMBER	MARK ON TOOL	SPEED IN FEET	DURATION OF CUT	CONDITION OF TOOL
14835	29PRL	58.8	10.0	G	14858	2709ME	60.5	20.0	G	14865	106PRL	50.0	40.0	G	14928	1945ME	46.75	49.0	R
14836	C1939ME	59.6	10.0	G	14859	196PRL	61.5	20.0	G	14866	128PRL	53.0	40.0	G	14931	C2739ME	51.5	80.0	G
14837	C1903ME	63.2	10.0	G	14860	170PRL	60.3	20.0	G	14867	102PRL	55.4	22.7	R	14933	C2092ME	49.9	80.0	G
14838	C2685ME	65.7	10.0	G	14861	106PRL	60.5	20.0	G	14868	115PRL	53.0	40.0	G	14935	C2757ME	52.5	80.0	G
14839	C2721ME	66.4	10.0	G	14862	C1945ME	61.0	20.0	G	14872	C1945ME	52.5	40.0	G	14936	128PRL	53.6	46.3	R
14840	C2709ME	71.1	10.0	G	14863	2709ME	63.4	9.0	R	14877	106PRL	56.3	40.0	G					
14841	C1939ME	72.5	4.8	R	14864	170PRL	62.5	18.1	R	14878	128PRL	56.25	40.0	G					
14842	C1903ME	70.0	5.5	R						14882	106PRL	55.2	14.4	R					
14843	C2721ME	70.0	3.8	R						14883	115PRL	55.25	40.0	G					
14844	C2685ME	67.5	1.8	R						14886	156PRL	54.3	12.1	R					
14845	C2709ME	70.0	2.0	R						14887	C1945ME	55.2	40.0	G					
Conclusion		67	10	6	Conclusion		62	20	6	Conclusion		56.5	40	6	Conclusion		51.5	80	6

Cutting Speed Figured by the Formula $V = \frac{90}{T^{\frac{1}{4}}}$

67'.5	61'.9	56'.7	52'

Chemical Composition of Forging

Carbon	0.34
Manganese	0.60
Silicon	0.183
Phosphorus	0.035
Sulphur	0.032

Physical Properties of Forging
Annealed at 1275°

Tensile Strength	71300
Elastic Limit	32590
Per Cent Extension	29.00
Per Cent Contraction	49.57

Chemical Composition of Tool No 27
Folder 20, Table 138

Tungsten	8.50
Chromium	2.00
Carbon	1.85
Manganese	0.15
Silicon	0.15
Phosphorus	
Sulphur	

Meaning of Following Symbols
G— Good
F— Fair
BR—Began to Ruin
R— Ruined

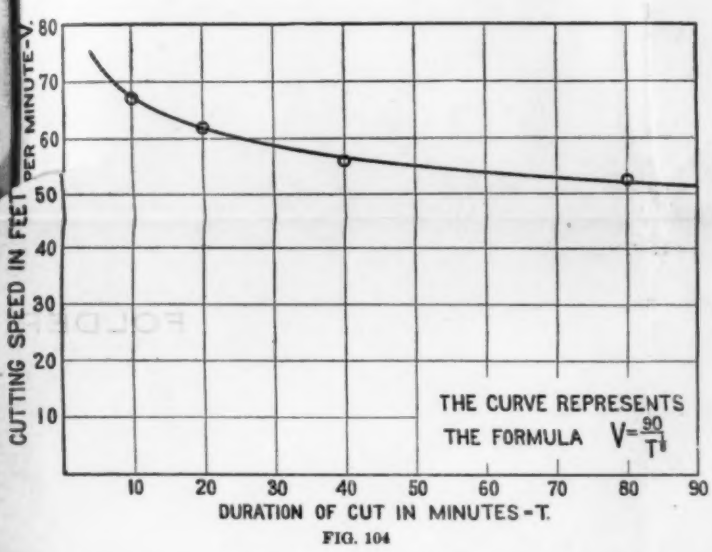


FIG. 104

DIAGRAM GIVING SUMMARY OF EXPERIMENTS IN TABLE 103

TABLE 105
PRACTICAL RULE

Showing how much a high speed tool must be slowed down in cutting speed in order to have it last a long time without regrinding

See Folder 15, Table 103, and paragraphs 697 to 701

IF WE HAVE THE PROPER CUTTING SPEED FOR A CUT LASTING	WE FIND THE SPEED FOR A CUT LASTING	BY DIVIDING BY	OR BY MULTIPLYING BY
20 minutes	40 minutes	1.09	0.92
40 minutes	80 minutes	1.09	0.92
20 minutes	80 minutes	1.19	0.84
40 minutes	20 minutes	0.92	1.09
80 minutes	40 minutes	0.92	1.09
80 minutes	20 minutes	0.84	1.19

Effect of Duration of Cut on Cutting Speed

Tables 103, 104, 105, 108, 109 all refer to the same set of experiments upon the effect on the cutting speed of the time the tool is to run before regrinding. (See paragraphs 696 to 705, also 710)

FIG. 106 AND TABLE 107 EFFECT ON CUTTING SPEED OF VARYING THE TIME TOOL IS UNDER CUT

See paragraphs 695 and 706 to 708

Experiments made with $\frac{7}{8}$" x $1\frac{1}{4}$" Carbon Tempered Round Nose Roughing Tool, clearance angle 5°, back slope 8°, side slope 14°, taking a $\frac{1}{16}$" *Depth of Cut.* See Folder 5, Fig. 24

Experiments plotted on logarithmic paper, see Folder 15, Fig. 106

Place and Date of Experiments: Midvale Steel Co., Nicetown, Philadelphia, Pa., 1883

Chemical Composition of Steel Tire

Carbon	.58
Manganese	.66
Silicon	.20
Phosphorus	.036
Sulphur	

Physical Properties of Steel Tire

Tensile Strength	118,543
Elastic Limit	
Per cent Extension	14.5
Per cent Contraction	

FIG. 106

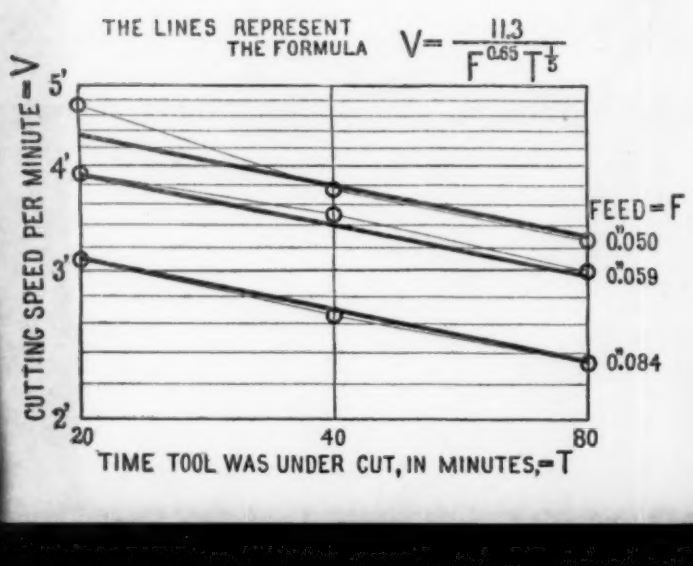


TABLE 107

T = TIME TOOL WAS UNDER CUT IN MINUTES	F = FEED IN INCHES	CUTTING SPEED FROM EXPERIMENTS IN FEET AND INCHES PER MINUTE	CUTTING SPEED BY THE FORMULA IN FEET PER MINUTE $V = \frac{11.3}{F^{0.65}T^{\frac{1}{2}}}$
20	0.050	4'— 8"	4'.35
	0.059	3'—11"	3'.9
	0.084	3'— 1"	3 .1
40	0.050	3'— 9"	3 .8
	0.059	3'— 6"	3 .4
	0.084	2'— 8"	2 .7
80	0.050	3'— 3"	3 .3
	0.059	3'— 0"	2 .96
	0.084	2'— 5"	2 .35

TA
The periods of tim
type)

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SIZE OF BODY OF TOOL IN INCHES	TIME TO REDRESS TOOL IN MINUTES	NUMBER OF REGRINDINGS
	8.8	13
	9.2	12
	9.7	11
	10.3	10
	11.0	10
	12.7	20
	14.8	20
	17.2	20
2 × 3	20.0	20

TABLE 110 EFFECT ON THE CUTTING SPEED OF A HEAVY STREAM OF WATER ON THE TOOL

See paragraphs 596 to 629

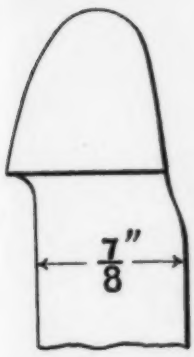
KIND OF TOOLS USED	QUALITY OF METAL BEING CUT, In all cases with depth of cut $\frac{3}{16}$" feed $\frac{1}{16}$"											
	EXTRA HARD STEEL BAR HAMMER HARDENED SEE M* BELOW			MEDIUM MACHINERY STEEL SEE F BELOW			LOCOMOTIVE TIRE STEEL SEE L BELOW			HARD CAST IRON SEE C BELOW		
HIGH SPEED CHROMIUM-TUNGSTEN TOOLS HEATED TO MELTING POINT	CUTTING SPEED IN FEET PER MINUTE		PER CENT OF GAIN THROUGH USE OF WATER	CUTTING SPEED IN FEET PER MINUTE		PER CENT OF GAIN THROUGH USE OF WATER	CUTTING SPEED IN FEET PER MINUTE		PER CENT OF GAIN THROUGH USE OF WATER	CUTTING SPEED IN FEET PER MINUTE		PER CENT OF GAIN THROUGH USE OF WATER
	DRY	WATER ON TOOL		DRY	WATER ON TOOL		DRY	WATER ON TOOL		DRY	WATER ON TOOL	
TOOLS H [ANALYSIS GIVEN BELOW] TOOLS B [ANALYSIS GIVEN BELOW]	16	22.33	41	60	83	39				47	54'7"	16
OLD STYLE SELF-HARDENING TOOLS MIDVALE SELF-HARDENING TOOLS							19'3"	25'11"	32			
CARBON TEMPERED TOOLS CONTAINING 1.6% CHROMIUM							15'4"	19'3"	25			

*Bar M was made especially so as to be as hard as any steel ever likely to be met with in ordinary machine shop practice. It was so hard that a Mushet self-hardening tool would run only at a cutting speed of 4 to 6 feet per minute with $\frac{5}{16}$" depth of cut and $\frac{1}{16}$" feed

The following are the chemical and physical properties of the above test pieces

BAR	CARBON	MANGANESE	SILICON	PHOSPHORUS	SULPHUR		TENSILE STRENGTH	ELASTIC LIMIT	PERCENTAGE OF STRETCH	PERCENTAGE OF CONTRACTION
M	1.05	0.86	0.147	0.27	0.034		102,270	71,590	1.00	0.75
F	0.34	0.54	0.176	0.037	0.026		70,000	34,000	29.00	44.00
L	0.555	0.981	0.236	0.049	0.310		115,000	58,000	15.6	31.4
C	3.32 total 1.12 comb.	0.680	0.860	0.780	0.073					

CLEARANCE 6°
BACK SLOPE 8°
SIDE SLOPE 14°



The following are the chemical compositions of the tools above referred to

NUMBERS OF THE TOOLS DESCRIBED IN FOLDERS 20, 21, 22		TUNGSTEN	CHROMIUM	CARBON	MANGANESE	SILICON	PHOSPHORUS	SULPHUR
26	TOOLS H	8.00	3.80	1.850	0.300	0.150		
2	TOOLS B	16.19	3.86	0.736	0.060	0.210		
70	MIDVALE SELF-HARDENING	7.723	1.83	1.143	0.180	0.246	0.023	0.009
84	CARBON TEMPERED		1.63	0.745	0.102	0.287	0.016	0.013

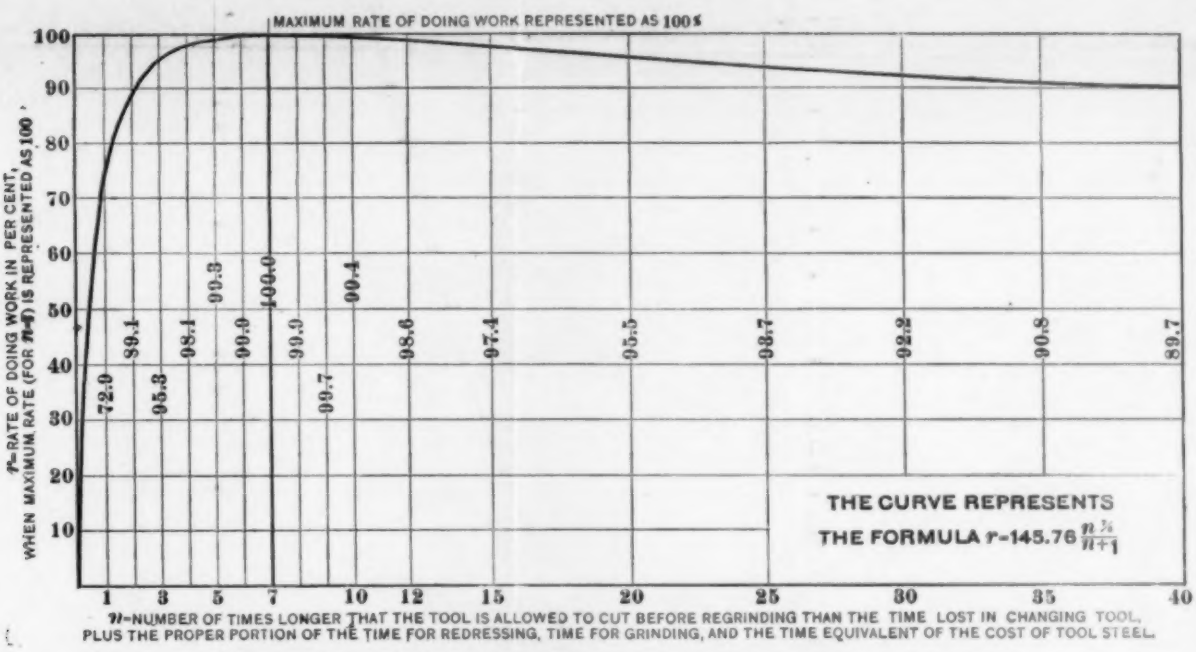

MAXIMUM RATE OF DOING WORK REPRESENTED AS 100
r-RATE OF DOING WORK IN PER CENT, WHEN MAXIMUM RATE (FOR n=7) IS REPRESENTED AS 100
72.0
89.1
95.3
98.1
99.3
99.9
100.0
99.9
99.7
99.4
98.6
97.4
95.5
93.7
92.2
90.8
89.7
THE CURVE REPRESENTS THE FORMULA r=145.76 n/(n+1)
n-NUMBER OF TIMES LONGER THAT THE TOOL IS ALLOWED TO CUT BEFORE REGRINDING THAN THE TIME LOST IN CHANGING TOOL, PLUS THE PROPER PORTION OF THE TIME FOR REDRESSING, TIME FOR GRINDING, AND THE TIME EQUIVALENT OF THE COST OF TOOL STEEL.

FIG. 109 HOW LONG A TOOL SHOULD RUN WITHOUT REGRINDING

This diagram shows that, in order to do the largest amount of work for the lowest all around cost, a tool should be allowed to cut continuously without grinding at least seven times the time lost in changing tool, plus the proper portion of the time for redressing, time for grinding and the time equivalent of the cost of the tool steel. (See paragraphs 710 to 728, Folder 15, Fig. 104, and Folder 15, Table 108)

TABLE 108 DATA FROM WHICH TO DECIDE HOW LONG EACH SIZED TOOL SHOULD BE RUN BEFORE BEING REGROUND

periods of time given in columns for Redressing, Grinding and Changing Tools, were determined by many stop-watch observations. In the column headed **t** (heavy faced type) are given the equivalent in the time of the machine operator and his machine of the total time for redressing, grinding and setting tool and the tool steel lost each time that the tool is reground

For description of the table, see paragraphs 710 and 728; also see Folder 15 or Fig. 109, and Folder 15, Tables 103 and 105. Table refers to our standard tools, Folder 5, Figs. 21a to 25e

TIME TO REDRESS TOOL IN MINUTES	NUMBER OF REGRINDINGS FOR EACH REDRESSING	PROPORTIONATE TIME OF REDRESSING FOR EACH REGRINDING IN MINUTES	A: PROPORTIONATE TIME OF REDRESSING FOR EACH REGRINDING CONVERTED INTO EQUIVALENT TIME FOR MACHINE	TIME TO GRIND TOOL IN MINUTES	B: TIME TO GRIND CONVERTED INTO EQUIVALENT TIME FOR MACHINE	COST OF TOOL STEEL LOST FOR EACH REDRESSING IN CENTS	COST OF TOOL STEEL FOR EACH REGRINDING IN CENTS	C: COST OF TOOL STEEL FOR EACH REGRINDING CONVERTED INTO EQUIVALENT TIME FOR MACHINE	D: TIME LOST IN CHANGING TOOL IN MACHINE IN MINUTES	t: EQUALS SUM OF COLUMNS A, B, C & D IN MINUTES	T − 7t: TIME TOOL MUST RUN BEFORE REGRINDING IN ORDER TO DO A MAXIMUM OF WORK TIME IN MINUTES	10t: TIME IN MINUTES	TIME WE RECOMMEND THAT TOOL BE RUN BEFORE REGRINDING, THAT IS, 10t IN EVEN FIGURES, IN HOURS AND MINUTES	SIZE OF BODY OF TOOL IN INCHES
8.8	13	0.677	1.130	2.2	3.67	9	0.69	1.38	1.5	**7.7**	54	77	1—15	¾ × ¾ × 1
9.2	15	0.613	0.766	2.4	3.00	17	1.13	1.69	1.6	**7.0**	49	70	1—15	¾ × ¾ × 1
9.7	17	0.571	0.571	2.6	2.60	30	1.76	2.11	1.7	**7.7**	54	77	1—15	¾ × ¾ × 1
10.3	18	0.572	0.477	2.8	2.33	47	2.61	2.61	2.8	**8.2**	57	82	1—30	¾ × ¾ × 1¼
11.0	19	0.579	0.414	3.0	2.14	70	3.68	3.16	3.0	**8.7**	61	87	1—30	1 × 1 × 1¼
12.7	20	0.635	0.353	3.6	2.00	137	6.85	4.57	3.3	**10.2**	71	102	1—45	1¼ × 1 × 1¼
14.8	20	0.740	0.336	4.3	1.95	236	11.80	6.44	3.6	**12.3**	86	123	2—00	1½ × 1½ × 2
17.2	20	0.860	0.331	5.1	1.96	375	18.75	8.66	4.0	**15.0**	105	150	2—30	1¾ × 1¾ × 2½
20.0	20	1.000	0.333	6.0	2.00	448	22.40	8.96	4.5	**15.8**	110	158	2—45	2 × 2 × 3

FIG. 111 TOOLS WITH STRAIGHT LINE CUTTING EDGES.

Showing (first) that with a straight cutting edge the chip is uniform in thickness throughout; (second) that with straight cutting edges the actual thickness of angle which the line of the cutting edge makes with the axis or center line of the work on lathe, and also with the thickness of the feed, and (third) the effect of cutting speed when the most elementary form of straight edged tool is used. For full shape, tools actually used, see Folder 7, Fig. 35. See paragraphs 292 a those recorded in Folder 16, Table 113

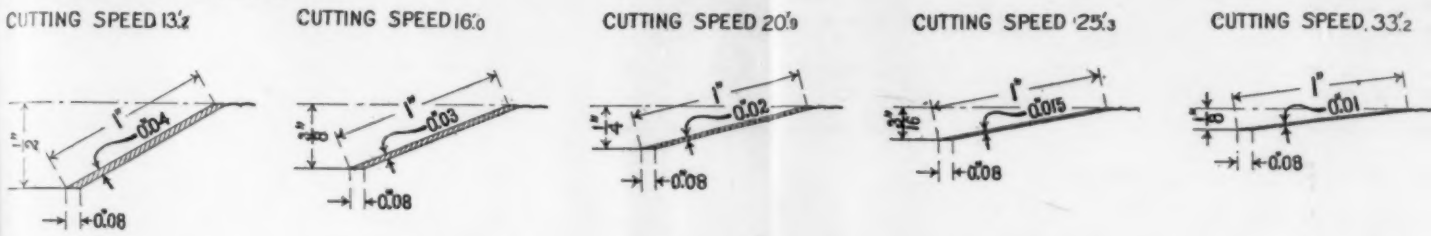


FIG. 112 WHY ROUND NOSED TOOLS ARE USED FOR ROUGHING WORK

Showing that with a curved cutting edge the thickness of the chip varies at all points and is thinner as it approaches the extreme nose of the tool; and round nosed tool the shaving is very thin at the point or nose, and that therefore a round nose tool insures against injury to the work even though it may b Folder 16, Fig. 111, and Folder 16, Fig. 113

See paragraphs 307 and 311

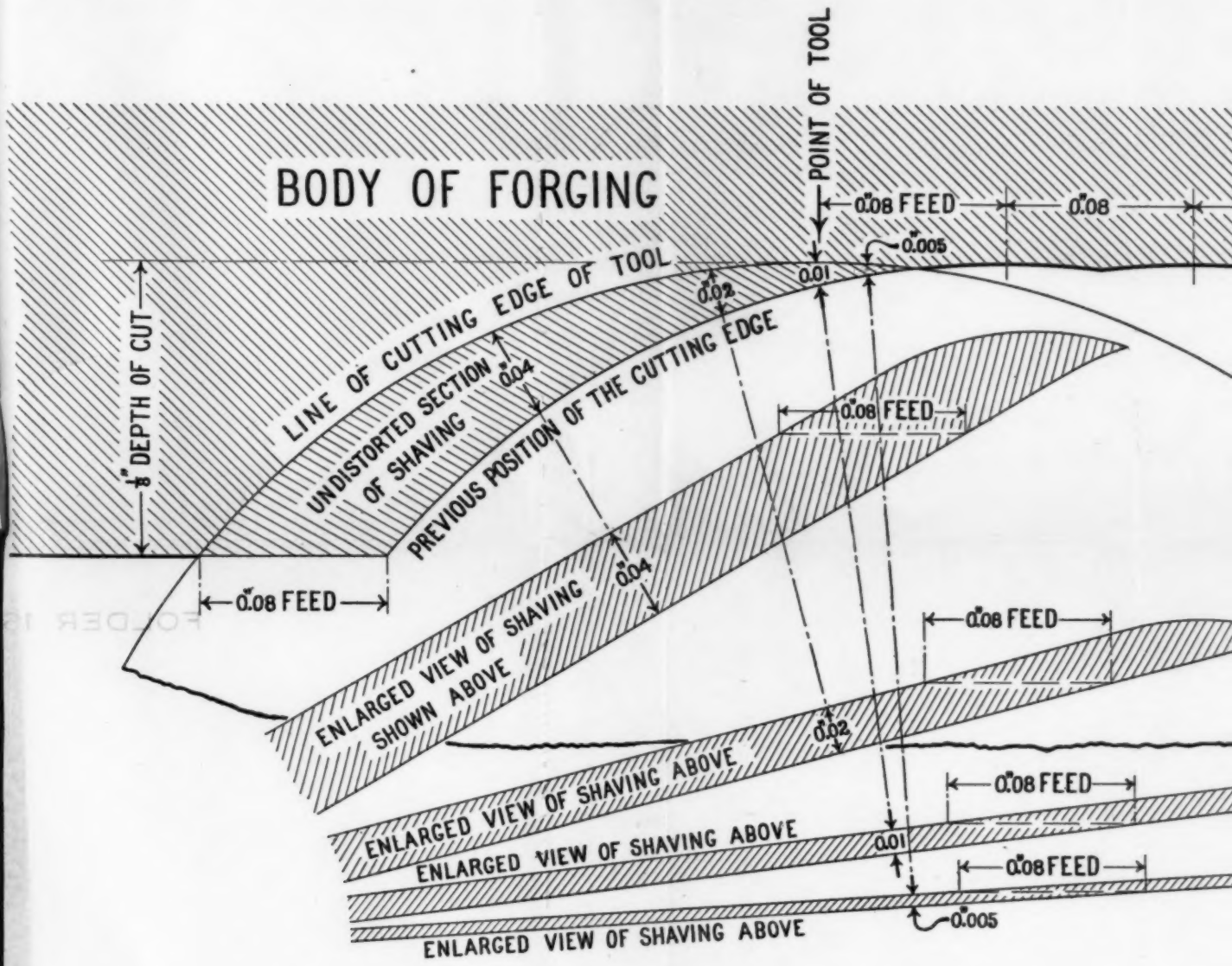


TABLE 113 TABLE ACCOMPANYING FIGS. 111, 114 AND 115

LENGTH OF SHAVING IN INCHES	DEPTH OF CUT IN INCHES	THICKNESS OF SHAVING IN INCHES	CUTTING SPEED, IN FEET, ON MEDIUM STEEL FORGING		CUTTING SPEED, IN FEET, ON HARD STEEL FORGING	
			FROM EXPERIMENTS	BY FORMULA $V=\frac{1.54}{t^{\frac{1}{3}}}$	FROM EXPERIMENTS	BY FORMULA $V=\frac{0.775}{t^{\frac{1}{3}}}$
	$\frac{1}{16}$	0.005		52.7	15.1†	15.3
	$\frac{1}{8}$	0.010	33.0	33.2	10.4	10.3
1	$\frac{3}{16}$	0.015	26.0*	25.3	8.8	8.2
	$\frac{1}{4}$	0.020	21.0	20.9	7.0	7.0
	$\frac{3}{8}$	0.030	16.0	16.0		5.6
	$\frac{1}{2}$	0.040		13.2		4.7

* One experiment only. † Two experiments only.

If we have the cutting speed for a shaving of a given thickness, we find the cutting speed for a shaving of:

	MEDIUM STEEL	HARD STEEL	AVERAGE
2 times the given thickness by multiplying by	0.63	0.67	0.65
3 times the given thickness by multiplying by	0.48	0.54	0.51
4 times the given thickness by multiplying by	0.40	0.46	0.43
$\frac{1}{2}$ the given thickness by multiplying by	1.59	1.48	1.53
$\frac{1}{3}$ the given thickness by multiplying by	2.08	1.86	1.97
$\frac{1}{4}$ the given thickness by multiplying by	2.52	2.18	2.35

Table 113 and Figs 115 Show the E Cutting Speed the Thickne Shavi

See paragraphs 29

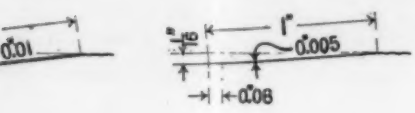
Experiments made with carbon, tempered 7, Fig. 35, with shaving in all cases exactly *o* water thrown on the tool

For the effect of varying the length of the constant, see Folder 17, Table 117, Figs. 116, 305

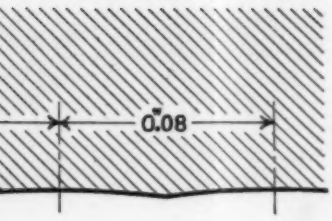
Place and date of experiments: MIDVALE

thickness of the chip varies according to the
the effect of thickness of shaving upon the
raphs 292 and 297. The speeds given are

EED. 33'.2 CUTTING SPEED 52'.7



he tool; and also showing that with a
gh it may be ruined under cut. See



d Figs. 111, 114 and the Effect on the Speed of Varying ckness of the Shaving

aragraphs 292 to 297

n, tempered straight edge tools shown in Folder
s exactly *one inch* long and a heavy stream of

ength of the shaving while the thickness is kept
7, Figs. 116, 118, 119. See paragraphs 299 to

s: MIDVALE STEEL CO., 1884

FIG. 114 CUTTING SPEED PLOTTED ON ORDINARY CROSS-SECTION PAPER

The upper curve represents the formula $V = \frac{1.54}{t^{\frac{1}{3}}}$ for Medium Forging

The lower curve represents the formula $V = \frac{0.775}{t^{\frac{1}{3}}}$ for Hard Forging

See paragraphs 292 to 297, Folder 16, Fig. 111, and Folder 16, Table 113

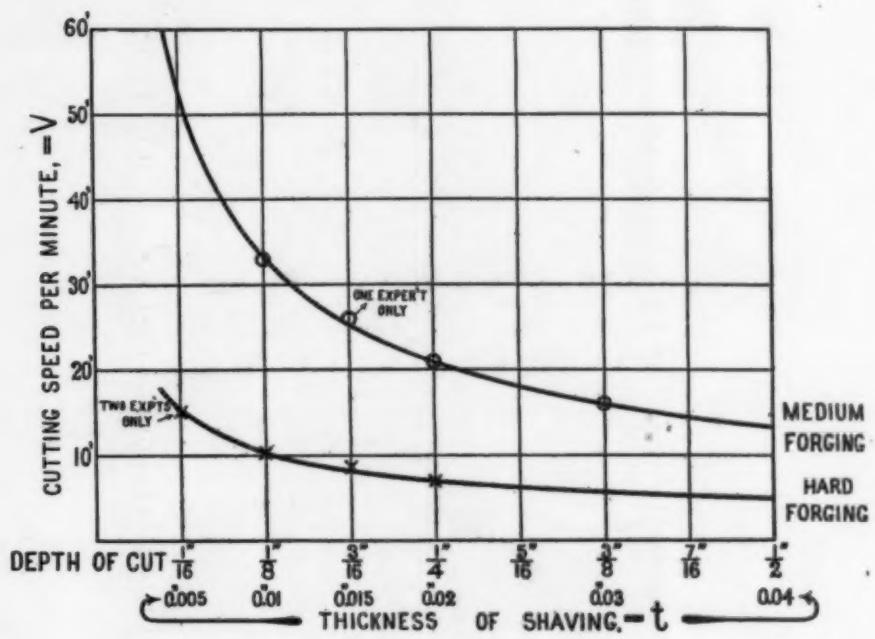


FIG. 115 CUTTING SPEED PLOTTED ON LOGARITHMIC PAPER

The upper straight line represents the formula $V = \frac{1.54}{t^{\frac{1}{3}}}$ for Medium Forging

The lower straight line represents the formula $V = \frac{0.775}{t^{\frac{1}{3}}}$ for Hard Forging

See paragraphs 292 to 297; Folder 16, Fig. 111, and Folder 16, Table 113

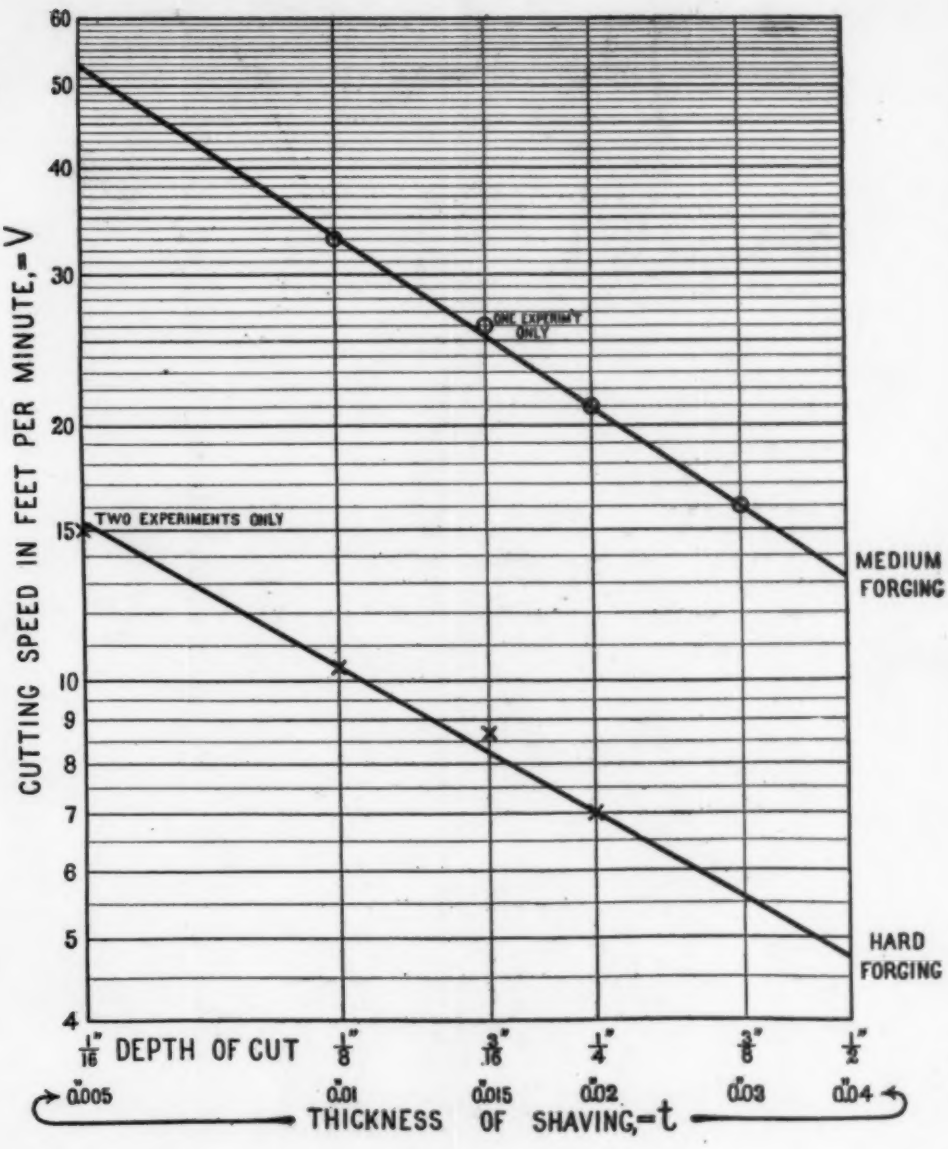


Fig. 116 Sketches showing effect of length of shaving (or depth of cut) on the cutting speed, when the most elementary form of straight edged tool is used For full shape of tools actually used, see Folder 7, Fig. 35. See paragraphs 299 and 305. Cutting speeds given are those recorded in Folder 17, Table 117

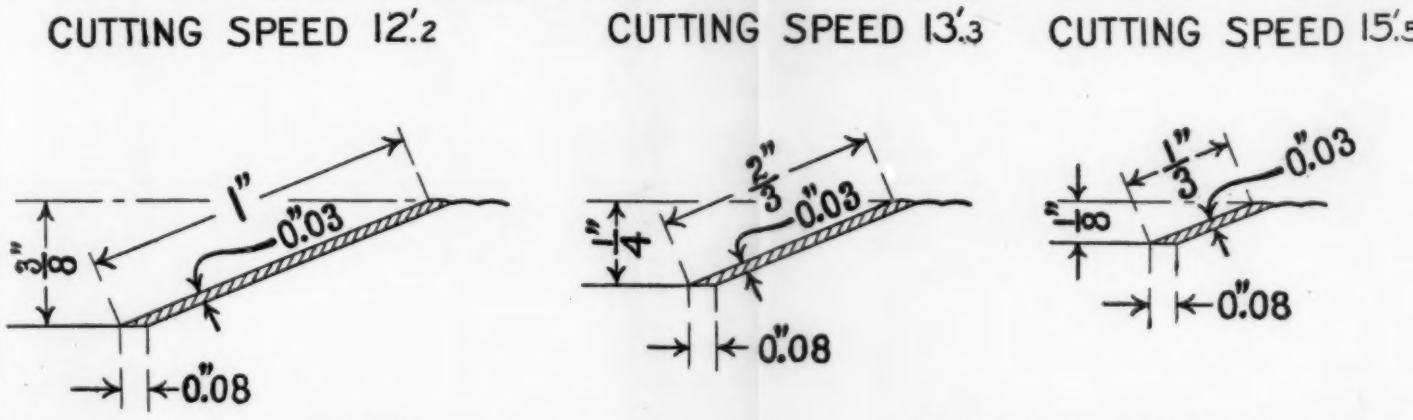


TABLE 117

THICKNESS OF SHAVING IN INCHES	DEPTH OF CUT IN INCHES	LENGTH OF SHAVING IN INCHES	CUTTING SPEED, IN FEET	
			FROM EXPERIMENTS	BY FORMULA $V=\frac{12'.2}{L^{\frac{1}{12}}}$
0.03	$\frac{1}{8}$	$\frac{1}{3}$	15.5	15.5
	$\frac{1}{4}$	$\frac{2}{3}$	13.33	13.3
	$\frac{3}{8}$	1	12.25	12.2
	$\frac{1}{2}$	$1\frac{1}{3}$		11.5

If we have the cutting speed for a shaving of a given length, we find the cutting speed for a shaving of:

2 times the given length by multiplying by	0.86
3 times the given length by multiplying by	0.79
4 times the given length by multiplying by	0.74
$\frac{1}{2}$ the given length by multiplying by	1.16
$\frac{1}{3}$ the given length by multiplying by	1.27
$\frac{1}{4}$ the given length by multiplying by	1.35

Fig. 118 Cutting speeds plotted on logarithmic paper. The straight line represents the formula $V=\frac{12'.2}{L^{\frac{1}{12}}}$

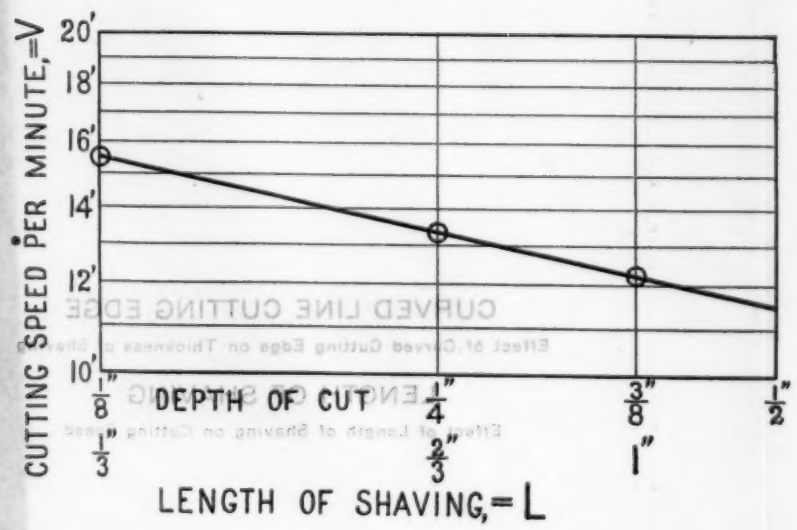


Fig. 119 Cutting speeds plotted on ordinary cross-section paper. The curve represents the formula $V=\frac{12'.2}{L^{\frac{1}{12}}}$

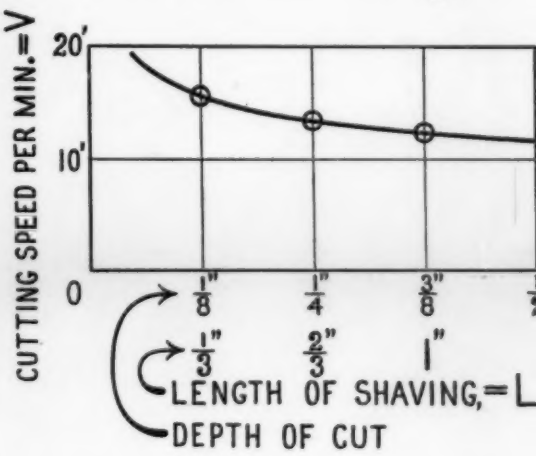


Table 117 and Figs. 116, 118 and 119 show the Effect on the Cutting Speed of the Length of the Shaving

Experiments made with carbon tempered straight edged tools shown on Folder 7, Fig. 35, with shavings in all cases 0.03 thick and with a heavy stream of water thrown on the tool

For the effect of varying the thickness of the shaving when the length is kept constant, see Folder 16, Table 113 and Figs. 111 and 114; also Folder 16, Fig. 112. See paragraphs 292 and 297

Place and date of experiments: MIDVALE STEEL CO., 1884

CHEMICAL COMPOSITION OF FORGING CUT

C	Mn	Si	P	S
0.492	0.477	0.194	0.042	0.0

PHYSICAL PROPERTIES, TEST BAR CUT FROM FORGING

Tensile Strength	97,719 pounds
Stretch	15 per cent
Contraction of Area	23.2 per cent

Fig. 120 Shapes or sections of chips cut by our Standard Round Nose Tools, enlarged 8 times (see Folder 5, Figs. 25a to 25d for ½ inch, ⅞ inch and 1¼ inch tools, all taking a feed of 1/16 inch. Note how much thinner the chip removed by the 1¼ inch tool is than ½ inch tool, particularly with shallow depths of cut. See paragraphs 325 and 1168. See Folder 16, Fig. 112

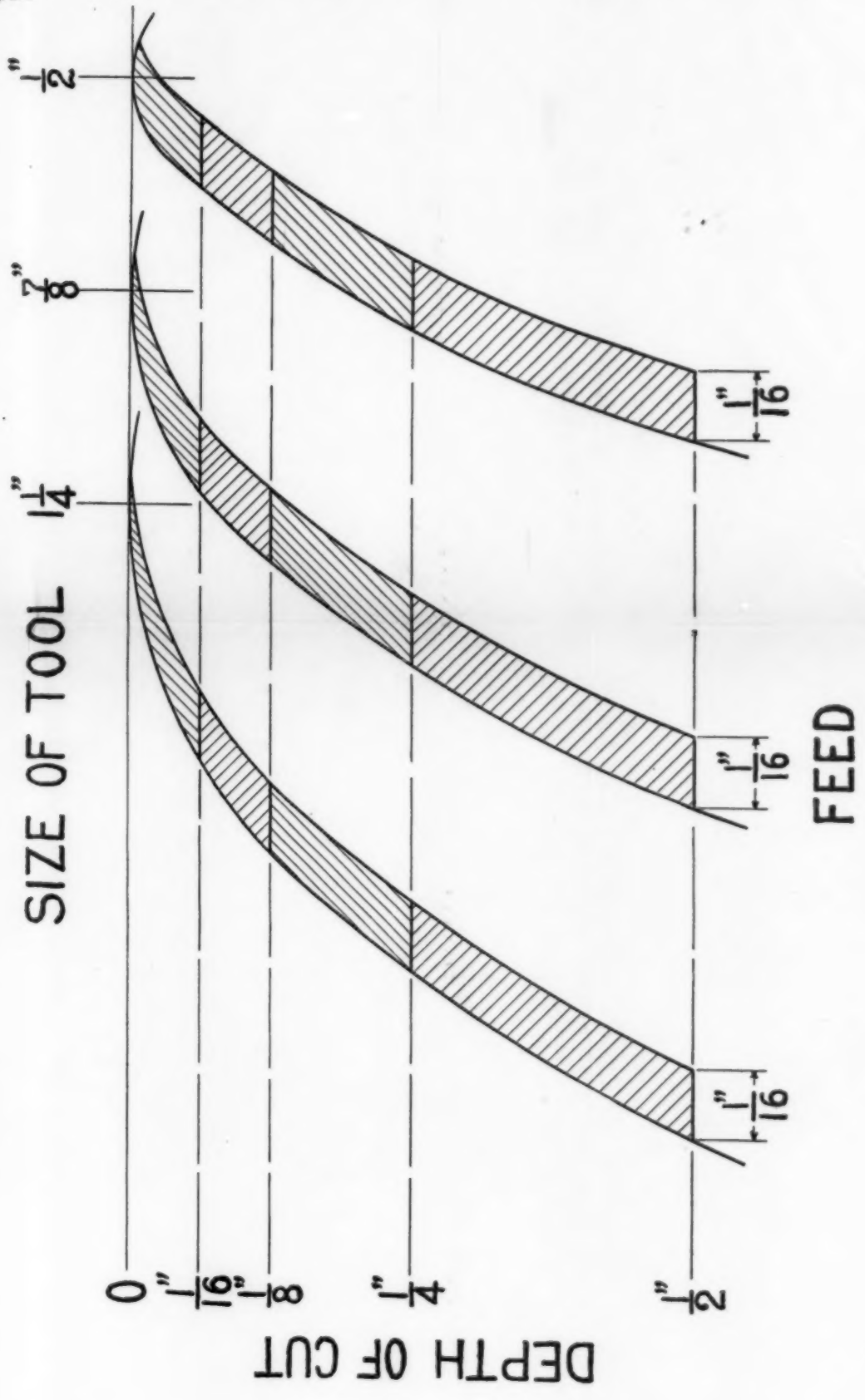
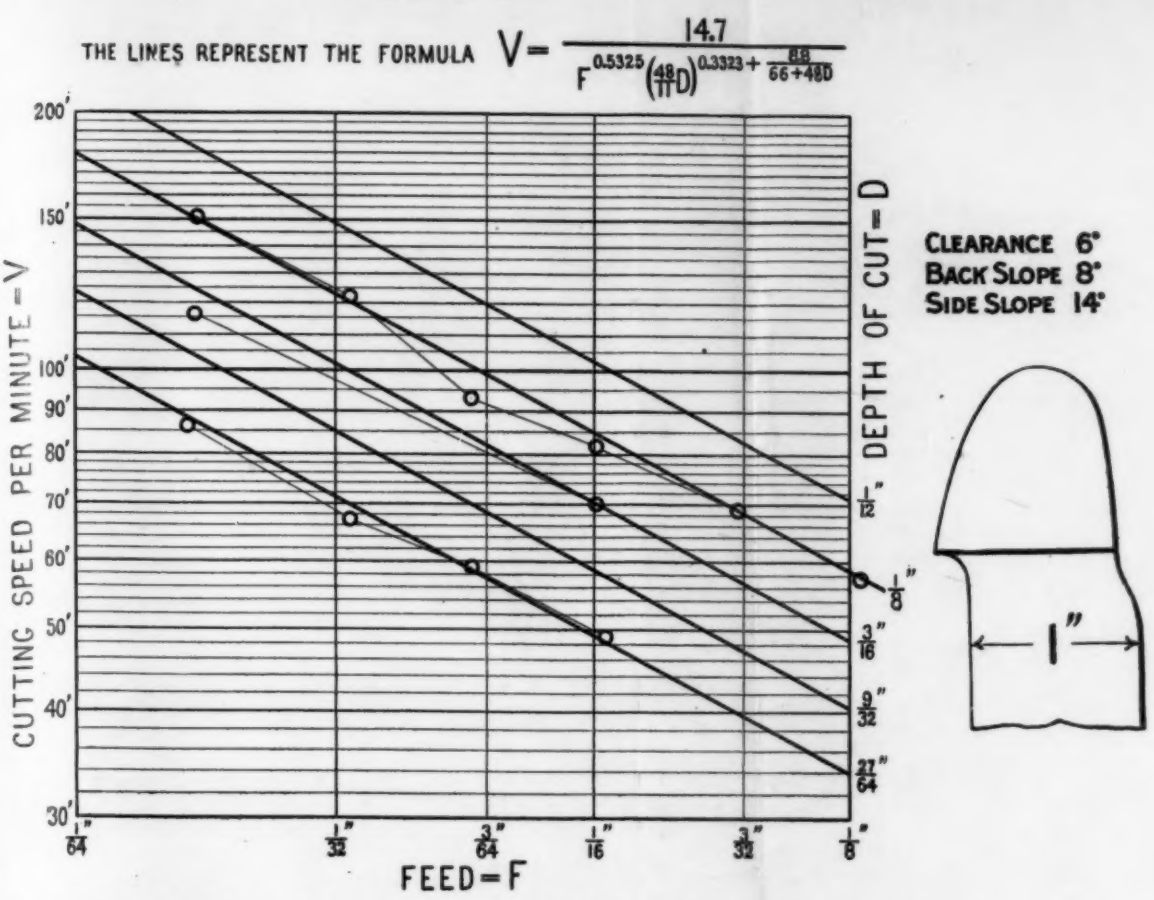


FIG. 125 Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Steel
See paragraph 787

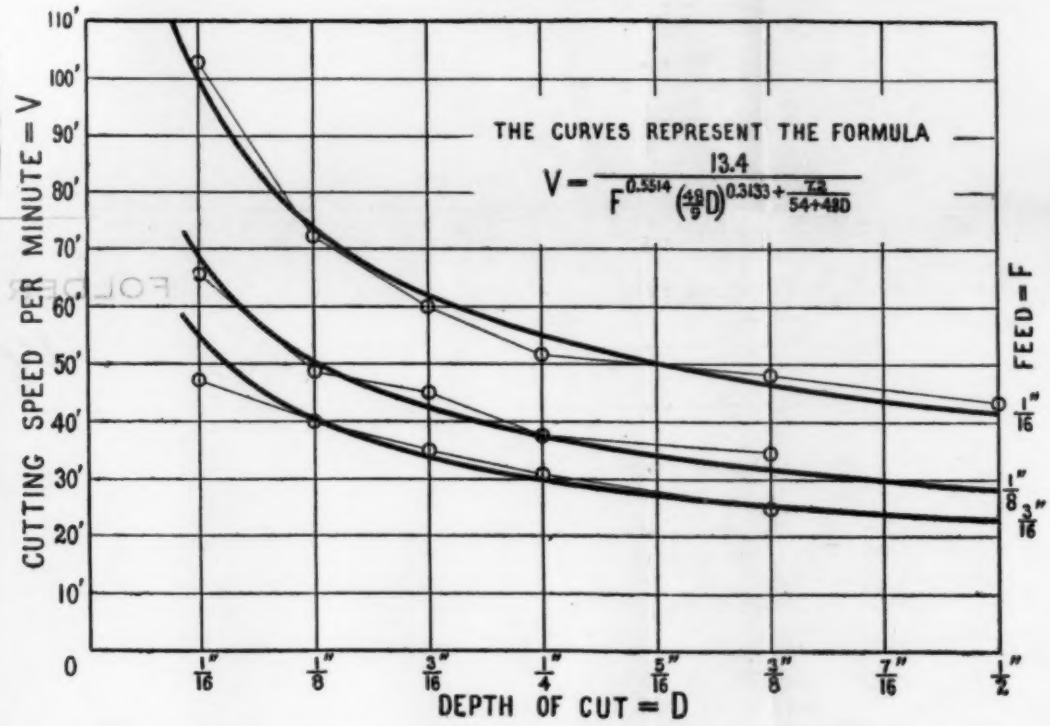


Experiments made with our Standard 1" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25a

Experiments plotted on ordinary cross-section paper. See Folder 18, Table 126

Place and Date of Experiments: Wm. Sellers & Co., Inc. Philadelphia, Pa., 1902

Fig. 127 Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Steel
See paragraphs 782 to 785



Experiments made with our Standard ¾" x 1¾" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 23

Experiments plotted on ordinary cross-section paper

For the same experiments plotted on logarithmic paper, see Folder 18, Fig. 128; see also Folder 18, Table 129

Place and Date of Experiments: Bethlehem Steel Co., South Bethlehem, Pa., 1900

TABLE 126 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN CUTTING STEEL
See paragraph 784

Experiments made with our Standard 1 inch x 1¼ inch Round Nose Roughing Tool, clearance angle 6 degrees, back slope 8 degrees, side slope 14 degrees. See Folder 5, Fig. 25a.

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET FROM EXPERIMENTS	CUTTING SPEED, IN FEET, BY THE FORMULA $V = \frac{14.7}{F^{0.5325}\left(\frac{48}{11}D\right)^{0.3323+\frac{8.8}{66+48D}}}$
1/8	0.0215	151	149.5
	0.0325	122	120.0
	0.0460	93	99.7
	0.0630	82	84.3
	0.0925	69	68.7
	0.1280	57½	57.8
3/16	0.0212	116	125.3
	0.0630	70	70.1
27/64	0.0210	86	88.3
	0.0325	67	69.9
	0.0450	59	58.8
	0.0645	49	48.6

For experiments plotted on logarithmic paper, see Folder 18, Fig. 125

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902

TABLE 131 EFFECT ON CUTTING SPEED OF VARYING OF CUT AND FEED IN CUTTING STEEL
See paragraph 789

Experiments made with our Standard ¼ inch x ¾ inch Round Tool, clearance angle 6 degrees, back slope 8 degrees, side slope Folder 5, Fig. 25a

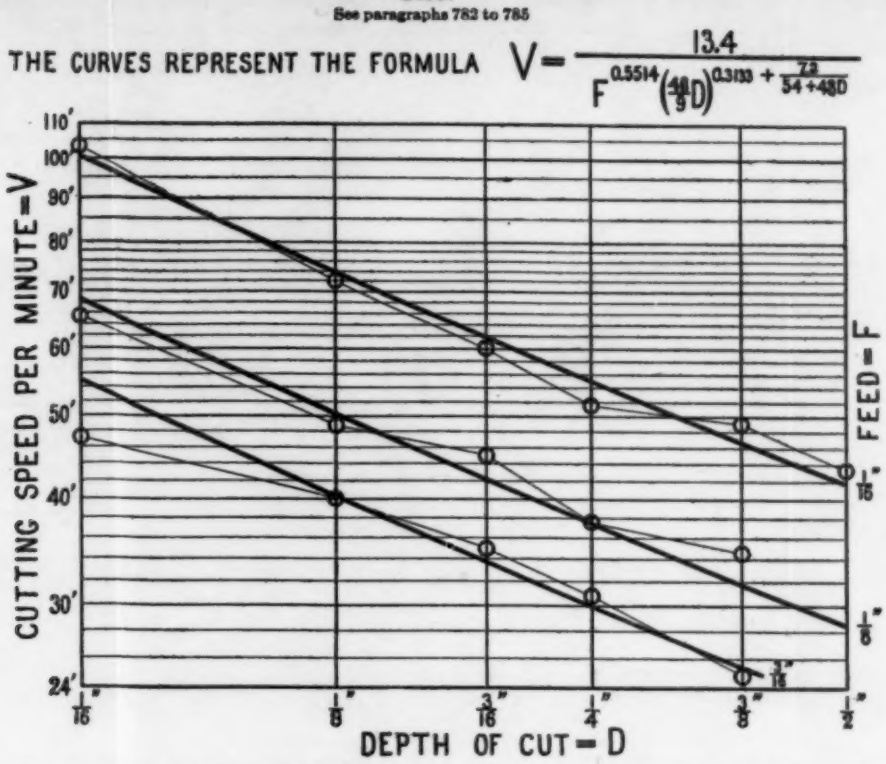
DEPTH OF CUT IN INCHES	FEED IN INCHES		CUTTING SPEED IN FEET PER MINUTE FROM EXPERIMENTS		CUTTI PER FOR FOL
1/12	0.015		174½		
	0.026		119		
	0.035		98		
	0.0458		86		
	0.0592		70		
1/8		0.0244		111	
	0.0255		115		
		0.033		99	
		0.046		73	
	0.046		71		
3/16		0.014		141	
		0.020		111	
	0.026		95		
		0.0318		82	
		0.0435		65	
	0.046		60		
		0.0625		50	

For experiments plotted on logarithmic paper, see Folder 18, Fig

Place and Date of Experiments: Wm. Sellers & Co., Inc., Phi

Fig. 128 Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Steel

See paragraphs 782 to 785



Experiments made with our Standard $\frac{1}{8}$" x $1\frac{1}{4}$" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 23

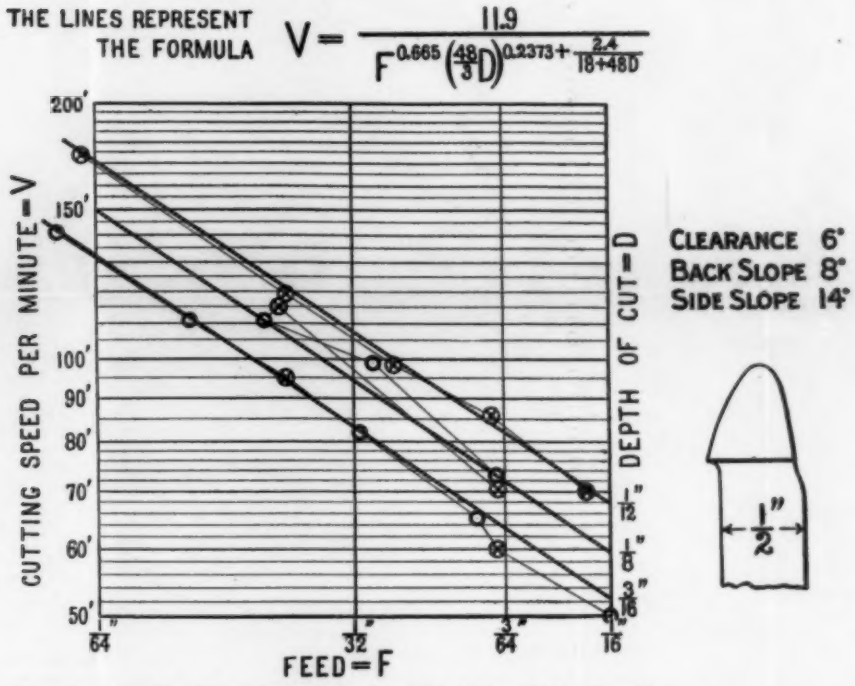
Experiments plotted on logarithmic paper

For the same experiments plotted on ordinary cross-section paper, see Folder 18, Fig. 127; see also Folder 18, Table 129

Place and Date of Experiments: The Bethlehem Steel Co., Bethlehem, Pa., 1900

Fig. 130 Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Steel

See paragraph 789



Experiments made with our Standard $\frac{1}{2}$ inch x $\frac{3}{4}$ inch Round Nose Roughing Tool, clearance angle 6 degrees, back slope 8 degrees, side slope 14 degrees, shown in Folder 5, Fig. 25a

Experiments plotted on logarithmic paper. See Folder 18, Table 131

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1902

TABLE 129 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN CUTTING STEEL

See paragraph 782

Experiments made with our Standard $\frac{1}{4}$ inch x $1\frac{1}{4}$ inch Round Nose Roughing Tool, clearance angle 6 degrees, back slope 8 degrees, side slope 14 degrees. See Folder 5, Fig. 23.

FEED IN INCHES	DEPTH OF CUT IN INCHES	CUTTING SPEED IN FEET FROM EXPERIMENTS	CUTTING SPEED, IN FEET, BY THE FORMULA $V=\frac{13.4}{F^{0.5514}\left(\frac{48}{9}D\right)^{0.3133+\frac{7.2}{54+48D}}}$
1/16	1/16	103.0	99.7
	1/8	72.0	73.6
	3/16	60.0	61.9
	1/4	51.6	54.8
	3/8	49.0	46.4
	1/2	43.3	41.6
1/8	1/16	65.5	68.1
	1/8	48.8	50.3
	3/16	45.0	42.2
	1/4	37.6	37.4
	3/8	34.6	31.7
3/16	1/16	47.1	54.5
	1/8	40.0	41.2
	3/16	35.0	33.7
	1/4	30.8	29.8
	3/8	24.8	25.3

For experiments plotted on logarithmic paper, see Folder 18, Fig 127

For experiments plotted on ordinary cross-section paper, see Folder 18, Fig. 128

Place and Date of Experiments: The Bethlehem Steel Co., South Bethlehem, Pa., 1900

For detail runs of the individual tools, see Folder 8, Table 45

VARYING THE DEPTH
G STEEL

inch Round Nose Roughing
side slope 14 degrees. See

EET	CUTTING SPEED, IN FEET PER MINUTE BY THE FORMULA SHOWN IN FOLDER 18, FIG. 130
	175.9
	122.0
	100.1
	83.7
	70.6
	111.3
	108.0
	91.0
	73.0
	73.0
	142.1
	112.1
	94.2
	82.4
	66.9
	64.4
	52.5

lder 18, Fig. 130
., Inc., Philadelphia, Pa.

FIG. 132 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN CUTTING CAST IRON

See paragraphs 810 and 811

Experiments made with our Standard ¾" x 1¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25b

These experiments were made in cutting cast iron, silicon 1.12

Experiments plotted on logarithmic paper. See Folder 19, Table 136

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1903

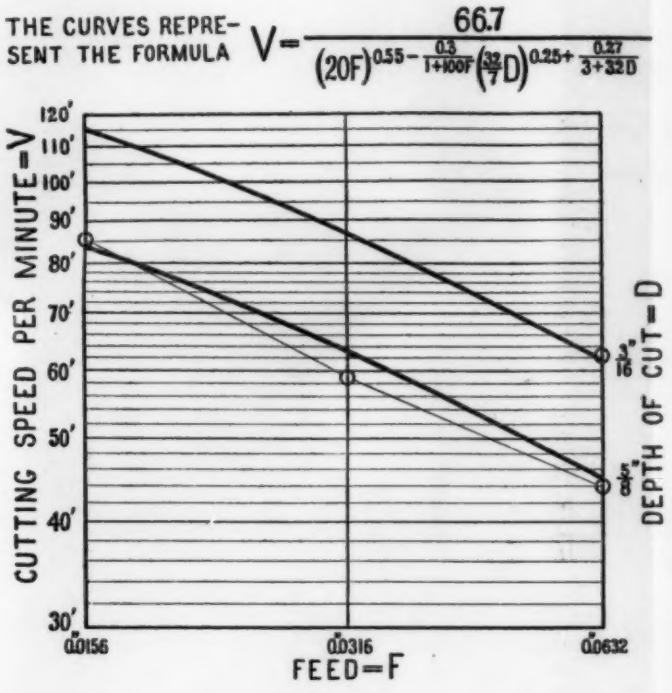


FIG. 133 EFFECT ON CUTTING SPEED OF VARYING THE DEPTH OF CUT AND FEED IN CUTTING CAST IRON

See paragraph 812

Experiments made with our Standard ¾"x 1¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25b

These experiments were made in cutting cast iron, silicon 1.20

Experiments plotted on logarithmic paper. See Folder 19, Table 136

Place and Date of Experiments: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1903

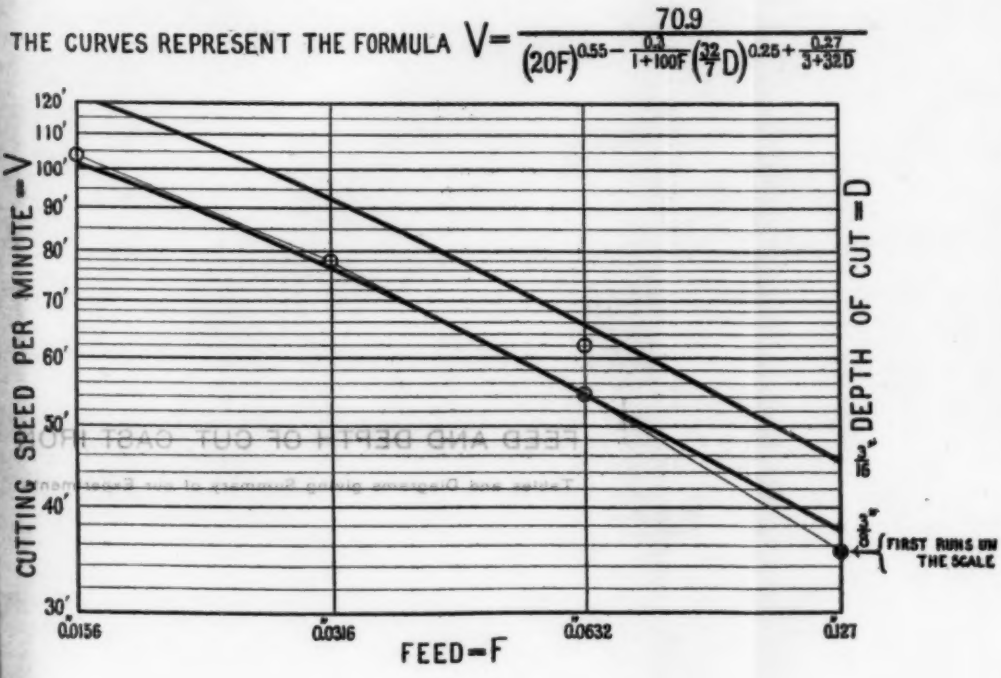
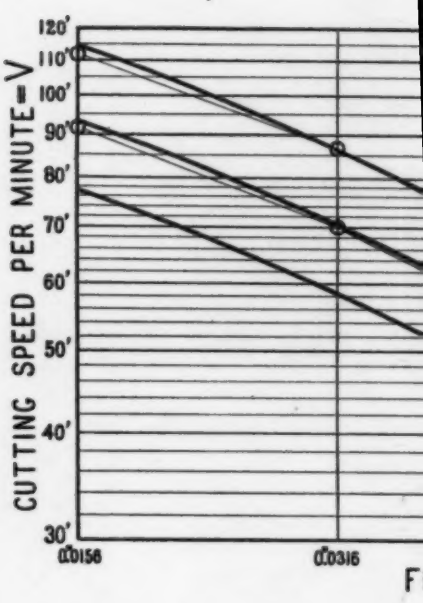
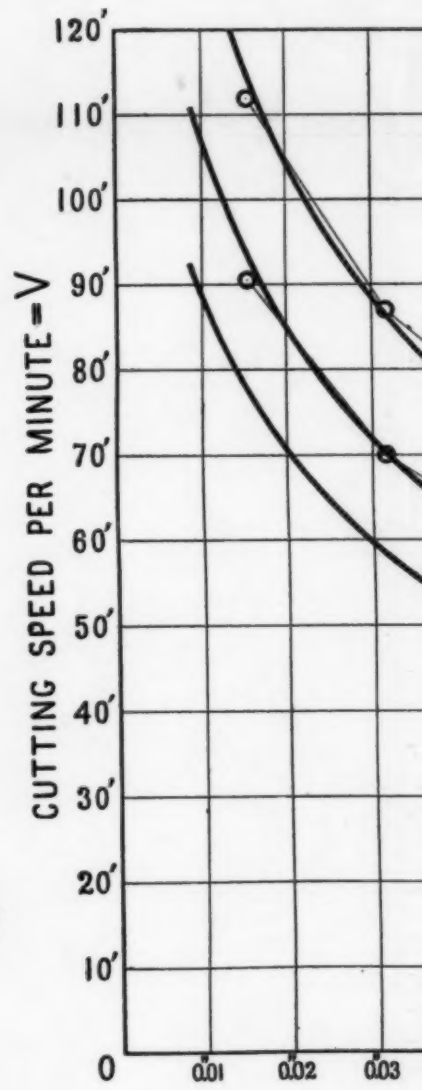


Fig.



Experiments made with our Standard ¾" ×1
Experiments plotted on logarithmic paper
For the same experiments plotted on ordinar
Place and Date of Experiments: Wm. Selli

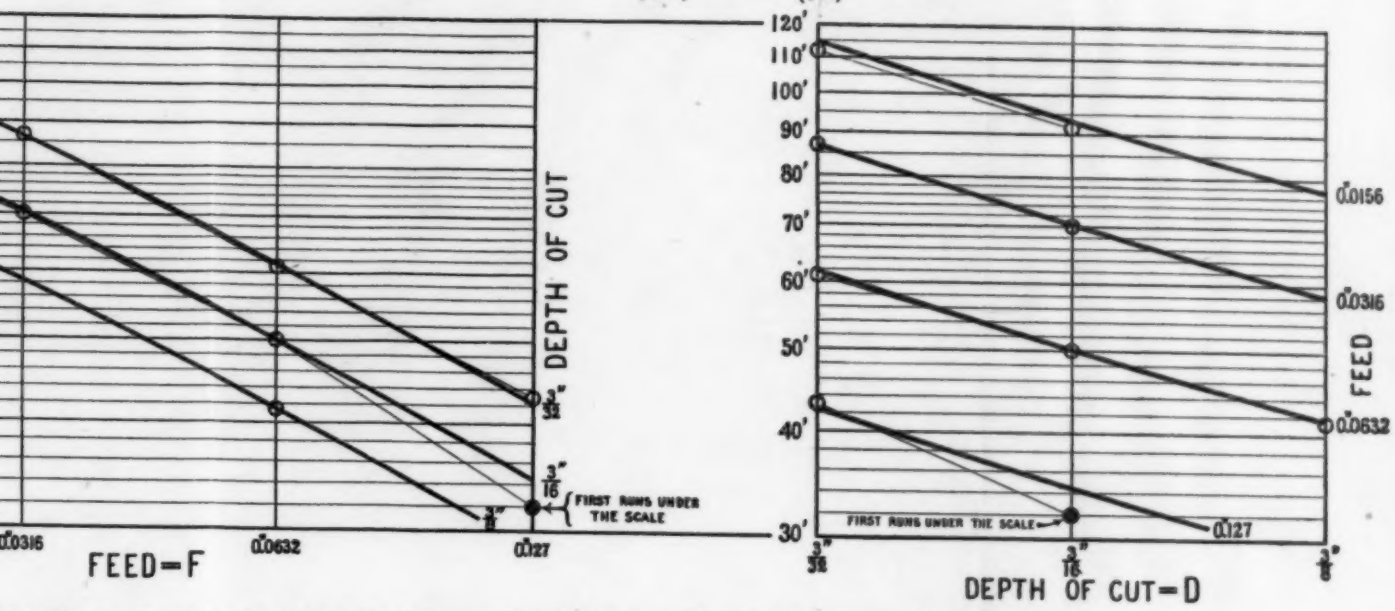
Fig. 135 Effect on Cuttin



Experiments made with our Standard ¾"
Folder 5, Fig. 25b
Experiments plotted on ordinary cross-s
For the same experiments plotted on logs
Place and Date of Experiments: Wm. S

Fig. 134 Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Cast Iron

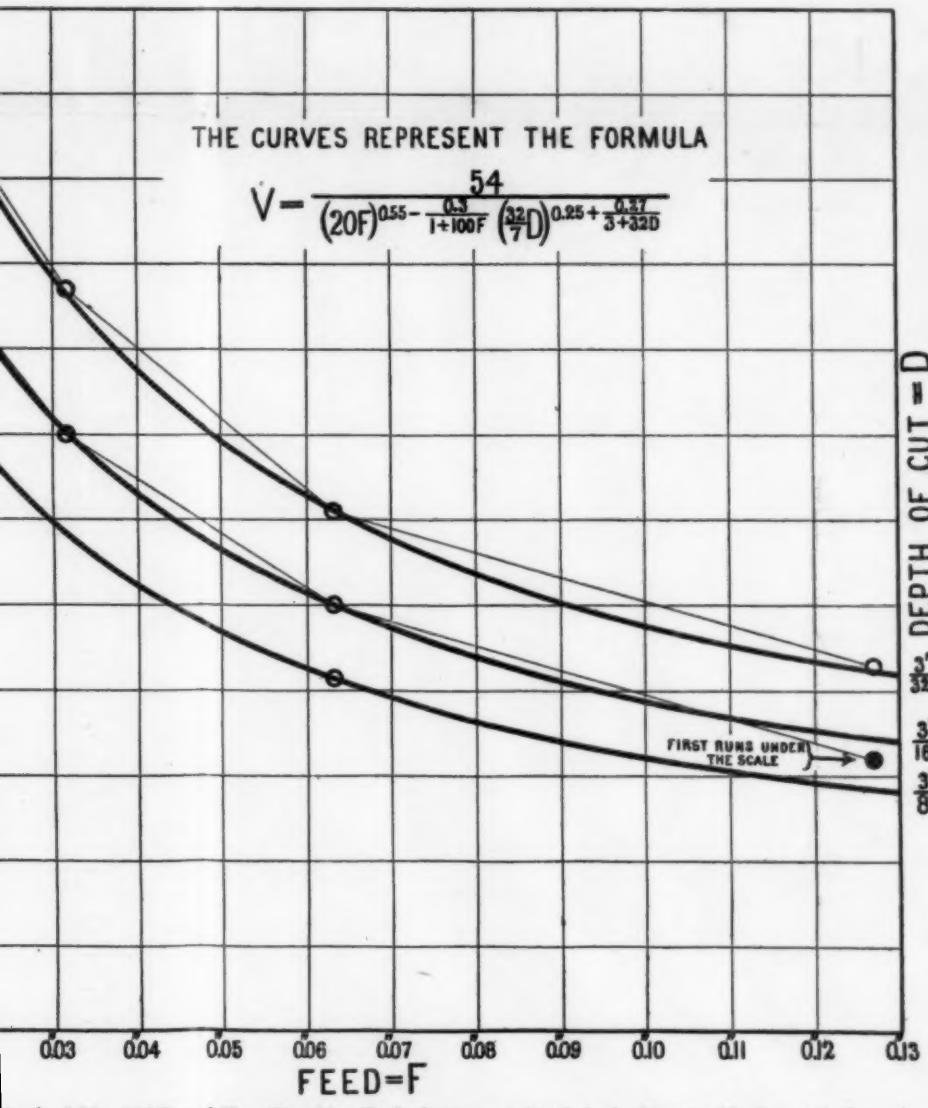
See paragraphs 805 and 806



dard ¾" ×1¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25b
nic paper
d on ordinary cross-section paper, see Folder 19, Fig. 135; see also Folder 19, Table 136
Wm. Sellers & Co., Inc., Philadelphia, Pa., 1903

t on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Cast Iron

See paragraphs 805 to 809



tandard ¾" x 1¼" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in
ary cross-section paper
ted on logarithmic paper, see Folder 19, Fig. 134; see also Folder 19, Table 136
s: Wm. Sellers & Co., Inc., Philadelphia, Pa., 1903

Table 136 Effect on Cutting Speed of

DEPTH OF CUT IN INCHES	FEED IN INCHES	CASTING OF 1.1% SILICON: CUTTING SPEED IN FEET PER MINUTE See Figs. 134 and 135 — FROM EXPERIMENTS	CASTING OF 1.1% SILICON: CUTTING SPEED IN FEET PER MINUTE See Figs. 134 and 135 — BY THE FORMU CONSTANT = 5
3/32	0.0156	112.0	114.8
	0.0316	87.0	86.3
	0.0632	61.0	61.5
	0.1270	43.0	42.4
3/16	0.0156	90.5	93.3
	0.0316	70.0	70.2
	0.0632	50.0	50.0
	0.1270	32.0	34.5
¼	0.0156		
	0.0316		
	0.0632	41.5	41.4
	0.1270		
½	0.0156		
	0.0316		
	0.0632		

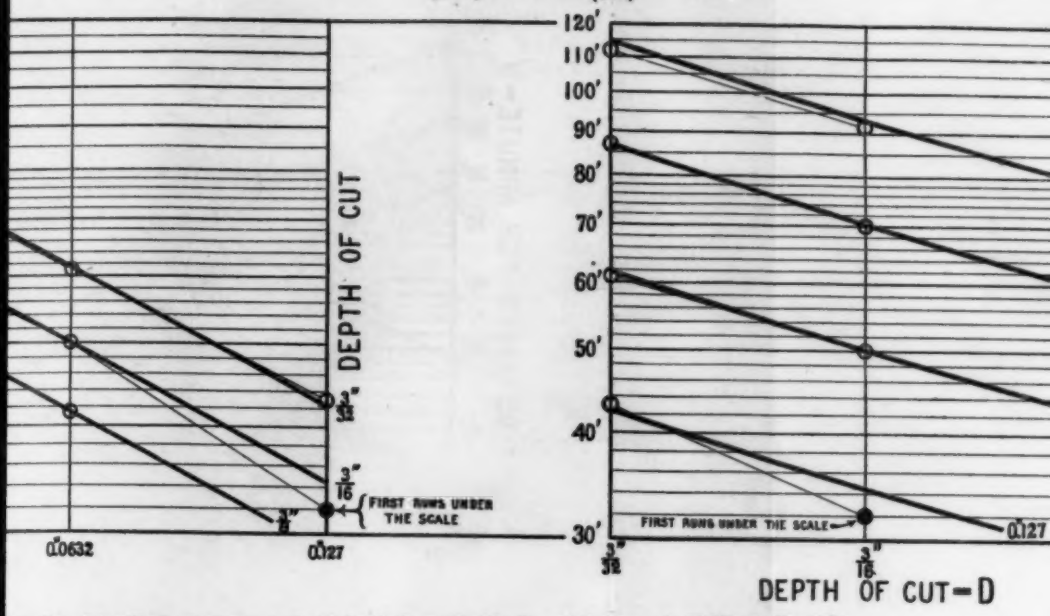
Experiments made with our Standard ¾" x 1¼" Rou
See Folder 5, Fig. 25b
For details of the experiments recorded in column 1
For experiments plotted on logarithmic paper, see
For experiments plotted on ordinary cross-section p
Place and Date of Experiments: Wm. Sellers &

These experiments are covered by the formula V

t on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Cast Iron

See paragraphs 805 and 806

REPRESENT THE FORMULA $V = \frac{54}{(20F)^{0.55-\frac{0.3}{1+100F}}\left(\frac{32}{7}D\right)^{0.25+\frac{0.27}{3+32D}}}$

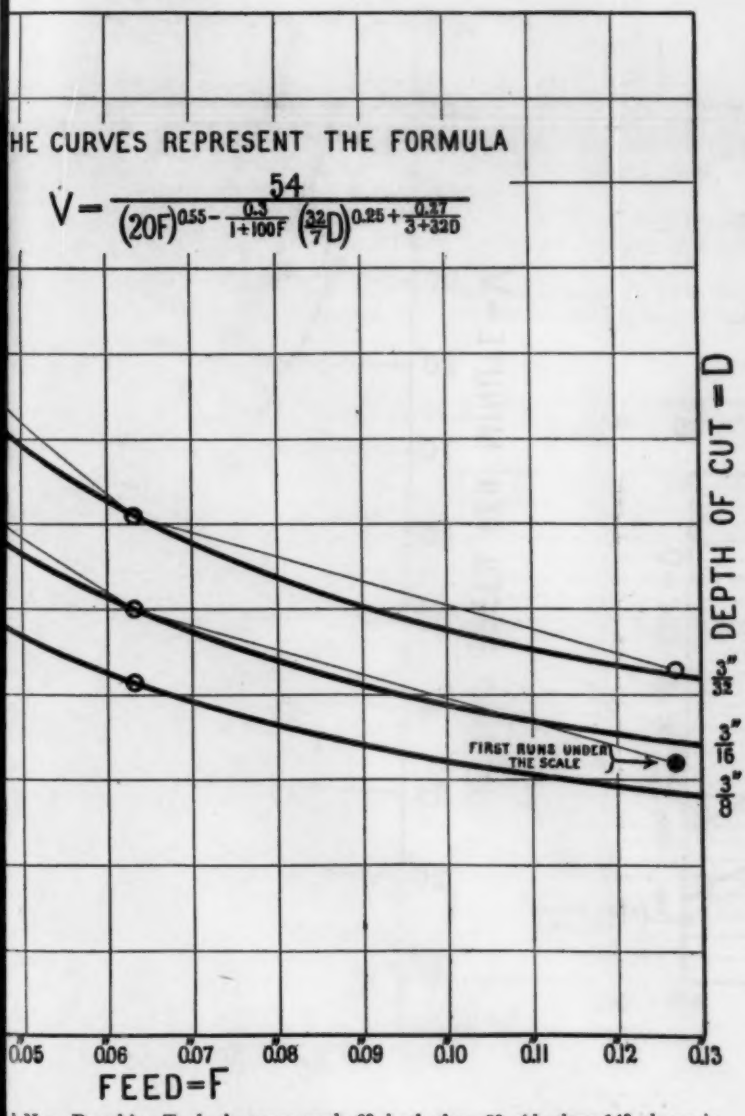


Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in Folder 5, Fig. 25b

ion paper, see Folder 19, Fig. 135; see also Folder 19, Table 136
NC., PHILADELPHIA, PA., 1903

f Varying the Depth of Cut and Feed in Cutting Cast Iron

See paragraphs 805 to 809



d Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°, shown in

r, see Folder 19, Fig. 134; see also Folder 19, Table 136
., INC., PHILADELPHIA, PA., 1903

Table 136 Effect on

DEPTH OF CUT IN INCHES	FEED IN INCHES	CASTING C CUTTING SI See F FROM EXPE MENTS
$\frac{1}{32}$	0.0156	112.0
	0.0316	87.0
	0.0632	61.0
	0.1270	43.0
$\frac{1}{16}$	0.0156	90.5
	0.0316	70.0
	0.0632	50.0
	0.1270	32.0
$\frac{1}{8}$	0.0156	
	0.0316	
	0.0632	41.5
	0.1270	
$\frac{1}{4}$	0.0156	
	0.0316	
	0.0632	

Experiments made with our St
See Folder 5, Fig. 25b
For details of the experiments
For experiments plotted on lo
For experiments plotted on or
Place and Date of Experimen

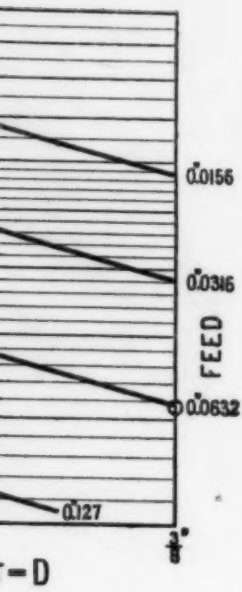
These experiments are covere

Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Cast Iron

See paragraphs 767 to 792

This entire folder refers to experiments on the effect on cutting speed of varying the depth of cut and feed in cutting cast iron.

For similar experiments on steel, see Folder 18



Effect on Cutting Speed of Varying the Depth of Cut and Feed in Cutting Cast Iron

See paragraphs 805 to 814

CASTING OF 1.1% SILICON		CASTING OF 1.12% SILICON		CASTING OF 1.2% SILICON	
CUTTING SPEED IN FEET PER MINUTE See Figs. 134 and 135		CUTTING SPEED IN FEET PER MINUTE See Fig. 132		CUTTING SPEED IN FEET PER MINUTE See Fig. 133	
FROM EXPERIMENTS	BY THE FORMULA CONSTANT = 54	FROM EXPERIMENTS	BY THE FORMULA CONSTANT = 66.7	FROM EXPERIMENTS	BY THE FORMULA CONSTANT = 70.9
112.0	114.8				
87.0	86.3				
61.0	61.5				
43.0	42.4				
90.5	93.3				
70.0	70.2				
50.0	50.0	63.5	61.8	62.0	65.7
32.0	34.5				
				104.0	101.5
				78.0	76.4
41.5	41.4			54.5	54.4
				35.5	37.5
		85.5	83.9		
		59.0	63.1		
		44.0	45.0		

with our Standard $\frac{3}{4}$" x $1\frac{1}{2}$" Round Nose Roughing Tool, clearance angle 6°, back slope 8°, side slope 14°.

xperiments recorded in column 1 of this table, see Folder 11, Table 67

lotted on logarithmic paper, see Folder 19, Figs. 132, 133 and 134

lotted on ordinary cross-section paper, see Folder 19, Fig. 135

Experiments: Wm. Sellers & Co., Philadelphia, Pa., 1903

are covered by the formula $$V = \frac{\text{Constant}}{\left(20F\right)^{0.55} - \frac{0.3}{1+100F}\left(\frac{32}{7}D\right)^{0.25} + \frac{0.27}{3+32D}}$$

TABLE 138 GIVING CHEMICAL COMPOSITIONS AND CUTTING SP

Including noted English, German, and American makes experimented upon by us in the summer and fall of 1906. Also Com
tools typical of various periods, from the Carbon

For further data, see paragraphs 1020 to 1094, and Folder 21, T

MARK ON TOOL		NUMBER OF THE TOOL STEEL	YEAR IN WHICH ANALYSIS WAS MADE	VANADIUM Va	MOLYBDENUM Mo	TUNGSTEN W	CHROMIUM Cr	CARBON C	MANGANESE Mn	SILICON Si	PHOSPHORUS P	SULPHUR S
	This is the best high speed tool with which we have experimented.....	1	1906	0.32 0.29		17.81 18.19	5.95 5.47	0.682 0.674	0.07 0.11	0.049 0.043		
	See paragraphs 1020 to 1034 Also paragraphs 1058 to 1094	2	1906			16.19	3.86	0.736	0.06	0.210		
		3	1906			14.41	3.28	0.709	0.07	0.120		
		4	1906			17.61	4.24	0.502	0.10	0.240		
		5	1906			14.23	3.44	0.739	0.06	0.165		
		6	1906			25.45	2.23	0.838	0.29	0.034		
		7	1906			14.91	5.71	0.790	0.06	0.060		
		8	1903		0.48	17.79	2.84	0.650	0.12	0.087	0.013	0.0
		9	1903			19.64	2.85	0.760	0.30	0.090		
		10	1903			18.99	2.61	0.670	0.20	0.265	0.014	0.0
		11	1903			23.28	2.80	0.800	0.11	0.165	0.015	0.0
		12	1903		2.03	18.93	3.52	0.580	0.19	0.125	0.029	0.0
		13			4.21	13.44	3.04	0.760	0.09	0.052		
		14	1905			24.64	7.02	0.600	0.03	0.205		
		15	1906			19.97	3.88	1.28	0.14	0.220		
		16	1906			19.16	5.61	0.79	low	low		
		17	1906		7.60	9.25	6.11	0.32	0.13	0.081		
		18	1906	0.28		16.00	3.50	0.70	low	low		
		19	1906			16.00	3.50	0.70	low	low		
		20	1903			14.71	2.90	0.700	0.12	0.196	0.017	0.0
		21	1903			15.31	2.88	0.540	0.12	0.133	0.018	0.0
		22	1903		0.75	14.91	2.80	0.450	0.10	0.090	0.018	0.0
		23	1903			14.62	2.81	0.600	0.18	0.323	0.017	0.0
		24			6.25		4.30	0.900	0.12	0.481	0.016	0.0
		25				10.68	3.67	1.160	0.10	1.340	0.024	0.0
	Typical Tools of Various Periods from the Carbo											
	Jessop Carbon (tempered)	85	1894					1.047	0.189	0.206	0.017	0.0
	Mushet (self-hardening) This tool was used by us in our Bethlehem experiments in 1898, referred to below as No. 65.....	65	1898			5.62	0.49	2.40	1.90	0.711	0.055	0.0
	Bethlehem (self-hardening Mesh). This tool was used by us in our Bethlehem experiments in 1898, referred to below as No. 27	27	1896			8.40	1.86	1.43	0.23	0.126		
	Bethlehem (self-hardening H S H). This tool was used by us in our Bethlehem experiments in 1898. Same as referred to below as No. 26. This was one of the tools used by us in experiments described in paragraphs 617 to 622. See paragraph 1033..	26				8.00	3.80	1.85	0.30	0.15	0.025	0.0
	Two tools of this composition were experimented with in 1906. One of these tools was used in our 1902 experiments, referred to in paragraph 805 and the other in tool steel experiments, made by us at the works of the Link Belt Engineering Co. in 1903. See No. 20 above	20	1903			14.71	2.90	0.70	0.12	0.196	0.017	0.
	Same tool used by us in tool steel experiments in works of Link Belt Engineering Co. in 1903. See No. 8 above	8	1903		0.48	17.79	2.84	0.65	0.12	0.087	0.013	0.
	Tool No. 1 above.....	1	1906	0.32 0.29		17.81 18.19	5.95 5.47	0.682 0.674	0.07 0.11	0.049 0.043		

*Tools marked thus were actually run in 1906 upon a 0.43 carbon forging which has a standard cutting speed as 48 ; 60 comp
†Tools marked thus were run on another forging or casting and the cutting speeds given were judged by comparing the quali
‡Tools marked thus were not run a sufficient number of times in this particular case to be certain of the correct speeds. The

Angles of Tools used on Medium Steel Forging, clearance angle
Angles of Tools used on Hard Steel Forging and Hard Cast Iro

Chemical Composition of Medium Steel Forging		Hard Steel Fo
Carbon	0.34	Carbon .....
Manganese	0.54	Manganese .....
Silicon	1.76	Silicon .....
Phosphorus	0.037	Phosphorus .....
Sulphur	0.026	Sulphur .....

Physical Properties of Medium Steel Forging	Tensile Strength	Elastic Limit	Per Cent of Ext
	70280 lbs.	34630	29
Hard Steel Forging	91670	60090	7
Test bars from each end of forging	101860	53980	5

UTTING SPEEDS OF THE BEST HIGH SPEED TOOLS

. Also Composition and Cutting Speeds of some of the Best High Speed Tools before 1906 and of Miscellaneous
n the Carbon Tool to the present day

d Folder 21, Table 139, and Folder 22, Table 140

PHOSPHORUS P	SULPHUR S	MEDIUM STEEL FORGING	HARD STEEL FORGING	HARD CAST IRON	
		99 ft. *	41 ft. 6 in.	52 ft.	Both of these analyses make tools of practically the same cutting speed. Forges hard at light cherry red. Should be forged at a light yellow heat, at which heat it forges more readily than the old self-hardening tools. (See paragraph 1068)
		91 ft. *	40 ft.	50 ft.	Rather hard to forge
			39 ft. ‡	50 ft.	Rather hard to forge
			38 ft. ‡	49 ft.	Rather hard to forge
			39 ft. 6 in.	46 ft.	Rather hard to forge
			39 ft.	47 ft.	Rather hard to forge
			38 ft. 6 in.	47 ft	Rather hard to forge
0.013	0.012	70 ft. †	37 ft.	45 ft. 6 in.	Rather hard to forge
			37 ft. †	45 ft. 6 in. †	Rather hard to forge
0.014	0.009		37 ft. †	45 ft. 6 in. †	Rather hard to forge
0.015	0.009		37 ft. †	45 ft. 6 in. †	Rather hard to forge
0.029	0.016		37 ft. †	45 ft. 6 in. †	Rather hard to forge
			37 ft. †	45 ft. 6 in. †	Rather hard to forge
		85 ft. *	38 ft. †	44 ft.	Rather hard to forge
		84 ft. *	38 ft. *		Rather hard to forge
		85 ft. *	37 ft. *		Rather hard to forge
		86 ft. *	37 ft. *		Rather hard to forge
			38 ft. *		Rather hard to forge
			34 ft *		Rather hard to forge
0.017	0.010	64 ft.	34 ft.	44 ft.	Rather hard to forge
0.018	0.009		34 ft. †	44 ft. †	Rather hard to forge
0.018	0.008		34 ft. ‡	44 ft. †	Rather hard to forge
0.017	0.009				Rather hard to forge
0.016	0.008				Cutting Speeds of these three steels inferior to any of the above
0.024	0.008				

n the Carbon Tool to the Present Day

0.017	0.017	16 ft.	6 ft.	15 ft. 6 in.	
0.055	0.051	26 ft.	8 ft. 6 in.	28 ft.	
		61 ft.	19 ft.	39 ft.	This tool was run both upon the 0.43 and 0.34 carbon forgings, referred to in footnote *, and gave cutting speeds of 48 feet and 60 feet, respectively. This tool was analyzed by us in 1906
0.025	0.030	58 ft.	30 ft. 6 in.	43 ft.	This tool was not again analyzed by us in 1906
0.017	0.010	64 ft. †	34 ft.	44 ft.	
0.013	0.012	70 ft. †	37 ft.	45 ft. 6 in.	
		99 ft. *	41 ft. 6 in.	52 ft.	

48 ; 60 compared to the cutting speed of the 0.34 carbon referred to in this column
ing the qualities of the two forgings or castings and the speeds of the other tools run at the same time
peeds. The figures given are therefore partly estimated

arance angle 6°, back slope 8°, side slope 14°
ard Cast Iron, clearance angle 6°, back slope 5°, side slope 9°

D STEEL FORGING		HARD CAST IRON	
.....	1.00	Carbon total	3.32
.....	1.11	Combined Carbon	1.12
.....	0.305	Manganese	0.68
s	0.036	Silicon	0.86
.....	0.049	Phosphorus	0.78
		Sulphur	0.073

CENT OF EXTENSION	PER CENT OF CONTRACTION	
29	44.34	
7	11.66	MINUTELY CRYSTALLINE, SLIGHT FLAW
5	9.73	MINUTELY CRYSTALLINE, SLIGHT FLAW

TABLE 139 GIVING THE CHEMICAL COMPOSITIONS AND CUTTING SPEEDS OF VARIOUS TOOLS USED BY US IN THE DISCOVERY A
HIGH SPEED TOOLS BY HEATING TOOLS CLOSE TO THE MELTIN

A study of the various groups of analyses will show the effects of Tungsten, Chromium, Molybdenum, Carbon and Manganese when used in large

For further data, see paragraphs 1042 to 1088, and Folder 20, Table 138, and Folder 22,

MARK ON TOOL		NUMBER OF THE TOOL STEEL	DATE ANALYSIS WAS MADE	MOLYBDENUM Mo	TUNGSTEN W	CHROMIUM Cr	CARBON C	MANGANESE Mn	SILICON Si	PHOSPHORUS P	SULPHUR S	MEDIUM STEEL FO: STANDARD SPEED OLD STYLE NOT TREATED T-W PROCESS	
	Recommended in patent for cutting hard steel....	26			8.00	3.80	1.85	0.30	0.150			27 ft.	58 ft
	Recommended in patent for cutting medium and soft metals	27			8.50	2.00	1.85	0.15	0.150			31 ft.	61 ft
		28			8.76	1.75	1.30	0.39	0.395			32 ft. 6 in.	61 ft
	Better Tools Made During Development of Taylor-White Process	29			8.38	1.62	1.26	0.31	0.432				60 ft
		30				2.01							60 ft
		31			7.89	2.16	0.858	0.47	0.288				61 ft
		32			6.50	2.77	1.860	1.19	0.379			32 ft.	61 ft
		33			6.83	3.94	1.470	0.37	0.770			27 ft.	61 ft
		34			7.68	3.78	1.810	0.32	0.191			20 ft. 11 in.	57 ft
		35			7.94	3.81	1.950	0.41	0.572				59 ft
	See paragraph 1045												
	Recommended in patent for cutting hard steel....	26			8.00	3.80	1.85	0.30	0.150			27 ft.	58 ft
		34			7.68	3.78	1.81	0.32	0.191			20 ft. 11 in.	57 ft
	Effect of High Chromium	35			7.94	3.81	1.95	0.41	0.572				59 ft
		33			6.83	3.94	1.47	0.37	0.770			27 ft.	61 ft
	See paragraph 1052												
		36			5.48	0.290	2.02	2.25	0.274			25 ft. 6 in.	39
		37			7.22	0.467	2.40	3.26	0.249			26 ft. 10 in.	37
		38			7.57	0.600	2.30	3.22	0.269			27 ft. 5 in.	37
		39			7.18	0.670	2.40	3.44	0.270			20 ft.	39
	Effect of Low Chromium	40			8.58	0.720	0.977	0.39	0.231			21 ft. 20 ft.	36 50
		41			0.83	3.80	1.80	2.19				27 ft.	23
	Effect of Low Tungsten	42			1.91	3.25	1.87	0.56				37 ft.	45
	See paragraph 1046	43		1.77		1.64	0.89	0.50				45 ft. †	58
	For effect of High Tungsten, see almost all other analyses	44		0.84		2.01	1.02	0.53				27 ft.	25
	Recommended in patent for cutting hard steel....	26			8.00	3.80	1.85	0.30	0.15			27 ft.	58
		35			7.94	3.81	1.95	0.41	0.572				59
	Effect of High Carbon	45			7.94	1.45	2.44	2.91	0.908				56
		46			8.05	2.61	2.27	0.42	0.792				57
	See paragraphs 1047 to 1050	32			6.50	2.77	1.86	1.19	0.379			32 ft.	61
		31			7.89	2.16	0.858	0.47	0.288				61
		40			8.58	0.72	0.977	0.39	0.231			20 ft.	50
	Effect of Low Carbon	47			7.87	1.00	1.200	0.41	0.291			30 ft.	50
		29			8.38	1.62	1.260	0.31	0.432				60
		48			3.55	1.91	1.290	0.42	0.235			23 ft. 8 in.	47
	See paragraphs 1048 to 1050	28			8.76	1.75	1.300	0.39	0.395			32 ft. 6 in.	61
	Effect of High Manganese	45			7.94	1.45	2.44	2.91	0.908				56
		49			8.61	1.40	1.14	2.38	0.980			22 ft. 6 in	
	See paragraphs 1051												
		50		4.20		3.95	1.18	0.08					60
		51			8.15	1.91	1.68	0.12	0.16			32 ft. 6 in.	55
		52			8.85	1.75	1.54	0.13	0.09				
	Effect of Low Manganese	53			8.41	3.29	1.54	0.24	0.32			25 ft.	50
		54		3.67		3.86	1.84	0.30	0.23			27 ft. 6 in.	60
		34			7.68	3.78	1.81	0.32	0.191			20 ft. 11 in.	57
		33			6.83	3.94	1.47	0.37	0.770			27 ft.	61
	See paragraph 1051												
		55		0.56			1.05	0.20	0.120			16 ft. 10 in.	
		56		0.84		2.01	1.02	0.53				27 ft.	3
		57		0.94			1.07	0.20	0.15			21 ft. 10 in.	
		43		1.77		1.64	0.89	0.50				45 ft. †	58
		58		2.03	4.53	2.03	2.02	1.69	0.282			31 ft. 36 ft.	58 58
	Molybdenum Substituted for Tungsten	59		2.25	4.74	2.80	2.07	1.66	0.120			36 ft.	58
		60		2.45		3.19	1.22	0.66	0.240			30 ft.	50
		54		3.67		3.86	1.84	0.30	0.230			27 ft 6 in.	60
		50		4.20		3.95	1.18	0.08					60
		61		4.58		3.43	1.61	1.65	0.285				59
		62		4.59		3.46	1.51	1.62	0.245			45 ft. 3 in.	
	See paragraph 1053	63		4.60		3.75	1.84	1.79	0.156			45 ft.	
	To Test Annealing Qualities	51			8.15	1.91	1.68	0.12	0.16			32 ft. 6 in.	5
		52			8.85	1.75	1.54	0.13	0.09				

*Tools marked thus. The record of their cutting speeds could not be found. Speeds given from memory

†Tools marked thus were run on another forging or casting and the cutting speeds given were judged by comparing the qualities of the two

COVERY AND DEVELOPMENT OF THE TAYLOR-WHITE PROCESS FOR MAKING
E MELTING POINT

sed in large or in small quantities upon the speeds of Taylor-White treated tools

d Folder 22, Table 140

M STEEL FORGING: T-W PROCESS	M STEEL FORGING: STANDARD SPEED TREATED T-W PROCESS	VERY HARD STEEL FORGING TREATED T-W PROCESS	HARD CAST IRON TREATED T-W PROCESS	
	58 ft.	20 ft. 6 in.	43 ft.	Considerably harder to forge than No. 27 just below
	61 ft.	19 ft.	39 ft.	Easy to Forge
in.	61 ft. 5 in,			This was one of the lot of tools used in the first series of experiments described in paragraphs 99 to 110, Part 1, which led to the discovery of the Taylor-White Process
	60 ft.			
	60 ft.			
	61 ft.			
	61 ft. 3 in.			
	61 ft. 3 in.			
1 in.	57 ft.			
	59 ft. *			
	58 ft.			
1 in.	57 ft.			
	59 ft. *			
	61 ft. 3 in.			
6 in.	39 ft. 3 in.			
10 in.	37 ft. 9 in.			
5 in.	37 ft.			
	39 ft. 10 in.			
	36 ft. 11 in.			
	50 ft.			
	23 ft.			
	45 ft.			
†	58 ft.			
	35 ft.			
	58 ft.			
	59 ft. *			
	56 ft. *			Hard to forge
	57 ft. *			
	61 ft. 3 in			
	61 ft.			
	50 ft.			
	50 ft.			
	60 ft.			
. 8 in.	47 ft. 2 in.			
. 6 in.	61 ft. 5 in.			
. 6 in	56 ft. *			Hard to forge
	60 ft.			Irregular
. 6 in.	55 ft.			
.	50 ft. 6 in.			
. 6 in.	60 ft.			Irregular
. 11 in.	57 ft.			
.	61 ft. 3 in.			
t. 10 in.				
t.	35 ft.			
t. 10 in.				
t. †	58 ft.			
ft.	58 ft. 4 in.			
ft.	58 ft. 4 in.			Tendency to fire crack
t.	58 ft. 4 in.			Tendency to fire crack
t.	50 ft.			
t 6 in.	60 ft.			Irregular
	60 ft.			Irregular
	59 ft.			Brittle in body and fire cracks eas ly
t. 3 in.				Brittle in body and fire cracks easily
t.				Brittle in body and fire cracks easily
t. 6 in.	55 ft.			Annealed readily
				Annealed readily

NOTES

ANGLES OF TOOLS USED

On Medium Steel Forging

Clearance Angle	6°
Back Slope	8°
Side Slope	14°

On Hard Steel Forgings And Hard Cast Iron

Clearance Angle	6°
Back Slope	5°
Side Slope	9°

CHEMICAL COMPOSITION

Medium Steel Forging

Carbon	0.34
Manganese	0.54
Silicon	1.76
Phosphorus	0.037
Sulphur	0.026

Hard Steel Forging

Carbon	1.00
Manganese	1.11
Silicon	0.305
Phosphorus	0.036
Sulphur	0.049

Hard Cast Iron

Carbon total	3.32
Combined Carbon	1.12
Manganese	0.68
Silicon	0.86
Phosphorus	0.78
Sulphur	0.073

PHYSICAL PROPERTIES

Medium Steel Forging

Tensile Strength	70280
Elastic Limit	34630
Per Cent Extension	29
Per Cent Contraction	44.34

Hard Steel Forging

Test bars cut from each end of forging

Tensile Strength	91670 / 101860
Elastic Limit	60090 / 53980
Per Cent Extension	7 / 5
Per Cent Contraction	11.66 / 9.73

Test bars minutely crystalline with slight flaw.

s of the two forgings or castings and the speeds of other tools run at the same time

TABLE 140 GIVING CHEMICAL COMPOSITION AND CUTTING SPEEDS OF VARIOUS SELF-HARDENING AND CARB

For further data, see paragraphs 1035 to 1045, and Folder 20

MARK ON TOOL	SELF-HARDENING TOOLS BEFORE THE DISCOVERY OF THE TAYLOR-WHITE PROCESS See paragraph 1041	NUMBER OF THE TOOL STEEL	YEAR IN WHICH ANALYSIS WAS MADE	MOLYBDENUM Mo	TUNGSTEN W	CHROMIUM Cr	CARBON C	MANGANESE Mn	SILICON Si	PHOSPHORUS P	SULPHUR S
	Mushet Steel	65	1898		5.62	0.490	2.40	1.90	0.711	0.055	0.051
	Atha and Illingsworth Self-hardening Steel	66	1898	4.58		3.430	1.615	1.65	0.285	0.027	0.016
S. S Co.	Firth Stirling Co	67	1898		7.57	0.600	2.300	3.22	0.269	0.019	0.007
M.S. Co.	Midvale Steel Co.	68	1898		8.48	1.460	1.386	0.32	0.358	0.016	0.022
X M	Sanderson S. H.	33			6.83	3.940	1.470	0.37	0.770		
	Sanderson Steel	69	1896		4.48	3.955	1.512	0.31	0.233	0.017	0.023
0 and 22	Midvale (self-hardening)	70	1894		7.723	1.830	1.143	0.18	0.246	0.023	0.009
00	Mushet (self-hardening)	71	1894		5.441	0.398	2.150	1.578	1.044		
X	Sanderson (self-hardening)	72	1894		4.537	2.410	1.400	0.324	0.216	0.018	0.006
I	Jonas and Colver (self-hardening)	73	1894		10.721	2.958	1.850	2.325	1.027		
	Burgess Special (self-hardening)	74	1894		7.599	0.074	2.320	3.530	0.630	0.036	0.004
	Mushet Air hardening Steel, Penna. Steel Co.	75	1893		6.057	0.342	2.213	1.800	0.883	0.037	0.023
	Stirling Steel Co. (self-hardening)	76	1893		8.387	0.254	1.806	1.870	0.156	0.018	0.009
	Sanderson (self-hardening)	77	1893		7.506	1.464	1.690	2.590	1.024	0.088	
	Sanderson (self-hardening)	78	1893		7.368	0.200	2.178	2.500	0.162	0.016	
	Sanderson (self-hardening)	79	1893		11.589	2.694	1.842	2.430	0.890	0.023	0.006
	Imperial (self-hardening) Park Bros., Pittsburg	80	1893		6.923	0.675	1.732	2.520	0.250	0.019	0.013
	Sanderson (self-hardening)	81	1893		7.975	1.325	1.625	2.670	0.976	0.072	0.013
	See paragraph 1036	**Tool Steels which contain either Tungsten or Chromium but which are not ever**									
P S	Pennsylvania Refining Co.	82	1894		1.842		1.376	0.552	0.255		
	Eichen Steel containing high tungsten but low manganese (not self-hardening)	83	1894		6.67 to 7.02	0.078	1.220	0.300	0.180	0.017	0.013
F and 1 x 1	Midvale Chrome Crucible Steel containing considerable chromium (not self-hardening)	84	1894			1.773 1.631	0.710 0.745	0.102	0.326 0.287	0.016 0.016	0.009 0.013
	See paragraph 1035	**Ordinary Carbon Tool Steels Hardened in**									
Z and III	Jessop (tempered)	85	1894				1.047	0.189	0.206	0.017	0.013
II	Stirling Special (tempered)	86	1894		0.079		1.240	0.156	0.232	0.016	0.009
IIII	Sanderson (tempered)	87	1894				1.072	0.291	0.148	0.014	0.013
S	Midvale Open Hearth (tempered)	88	1894				0.992	0.318	0.256	0.037	0.023
XO	(tempered)	89					0.681	0.198	0.219	0.024	0.013

*Tools marked thus. The record of their cutting speeds could not be found. Speeds are given from memory

†Tools marked thus were run on another forging or casting and the cutting speeds given were judged by comparing the qualities of the two

Angles of Tools used on Medium Steel Forging, clearance angle

Angles of Tools used on Hard Steel Forging and Hard Cast I

CHEMICAL COMPOSITION OF MEDIUM STEEL FORGING

Carbon	0.34
Manganese	0.54
Silicon	1.76
Phosphorus	0.037
Sulphur	0.026

	TENSILE STRENGTH	ELASTIC LIMIT	PER C
PHYSICAL PROPERTIES OF MEDIUM STEEL FORGING	70280 lbs.	34630	
HARD STEEL FORGING	91670	60090	
Test bars cut from each end of Forging	101860	53980	

AND CARBON TOOLS EXPERIMENTED WITH BY US PRIOR TO OUR DISCOVERY OF HIGH-SPEED TOOLS

nd Folder 20, Table 138, and Folder 21, Table 139

PHOSPHORUS P	SULPHUR S	MEDIUM STEEL FORGING STANDARD SPEED NOT TREATED AT A HIGH HEAT	HARD STEEL FORGING	VERY SOFT CAST IRON	
.055	0.051	26 ft. *			
.027	0.016	24 ft. *			Tendency to fire crack
.019	0.007	24 ft. *			
.016	0.022	30 ft. *			
.017	0.023	27 ft. *			
.023	0.008	25 ft. 8 in. †	10 ft. 11 in.†	89 ft.	Easier to forge than Mushet but liable to injury through overheating without crumbling as Mushet does
		25 ft. †	7 ft. 9 in.†	86 ft.	
.018	0.006	24 ft. 10 in†	8 ft.†	81 ft.	
		21 ft. 6 in. †	6 ft. 10 in.		Very hard to forge and brittle in the body
.036	0.004				
.037	0.023				
.018	0.008				
.088					
.016					
.023	0.007				
.019	0.014				
.072	0.011				

are not even in a small degree Self-Hardening Steels (Must be Hardened in Water)

.017	0.010				Must be hardened at a low heat or is likely to be brittle
.016	0.008				
.016	0.013	18 ft. †	7 ft. †	71 ft.	Requires rather low heat for hardening or is in danger of fire cracking

Hardened in Water

.017	0.017	16 ft. †	6 ft	47 ft. 6 in.	
.016	0.006	16 ft. †	5 ft. 11 in.	47 ft.	
.014	0.011	15 ft. 8 in. †		48 ft. 6 in.	
.037	0.020	16 ft. 8 in. †		48 ft.	
.024	0.011			47 ft.	

es of the two forgings or castings and the speeds of other tools run at the same time

rance angle 6°, back slope 8°, side slope 14°

Hard Cast Iron, clearance angle 6°, back slope 5°, side slope 9°

HARD STEEL FORGING

Carbon	1.00
Manganese	1.11
Silicon	0.305
Phosphorus	0.036
Sulphur	0.049

PER CENT OF EXTENSION	PER CENT OF CONTRACTION	
29	44.34	
7	11.66	MINUTELY CRYSTALLINE, SLIGHT FLAW
5	9.73	MINUTELY CRYSTALLINE, SLIGHT FLAW

TABLE 141 SHOWING EFFECT OF QUALITY OF METAL BEING CUT UPON THE CUTTING SPEED

See paragraph 1145

The chemical analyses given were made from drillings taken from the forging close to where the test bars were cut out which give the physical properties. The test bars were standard 2 inch x ½ inch bars, cut longitudinally from each end of the forging at such positions with relation to the axis of the forging as to give the average physical properties.

The cuts on these forgings were actually taken with our standard ¾ inch tool (Folder 5, Fig. 24) of the quality shown in tools 27 and 26, Folder 21, using standard 20-minute cut, $\frac{1}{16}$ inch depth of cut, $\frac{1}{16}$ inch feed.

In adjoining column will be found the corresponding cutting speeds which we believe would be obtained with the best high speed tool, as shown in tool No. 1, Folder 20.

In adjoining column are given the cutting speeds as figured for No. 1 tool by the empirical formula developed by us, shown in the heading of the column.

CHEMICAL COMPOSITION					ANNEALING HEAT IN DEGREES	PHYSICAL PROPERTIES				STANDARD CUTTING SPEED IN FEET PER MINUTE FOR TOOL MARK AS NUMBERED BELOW IN FOLDER 20, TOOL NO. 1, FOLDER 21, TOOLS 27 AND 26			STANDARD CUTTING SPEED FOR TOOL NO. 1 AS FIGURED BY THE FORMULA $V = \frac{125\left(1-\frac{215}{(15+E)^3}\right)}{\sqrt{\frac{S}{1000}}-3-0.9}$
C	MN	SI	P	S		TENSILE STRENGTH	ELASTIC LIMIT	PER CENT OF EXTENSION	PER CENT OF CONTRACTION	NO. 27	NO. 26	NO. 1 ESTIMATED	
0.105	0.25	0.008	0.04	0.008	1290	48570	24540	37.00	59.12	150		247.5	
						47870	24440	41.00	64.95				
0.105	0.36	0.025	0.035	0.023	1400	51440	24440	38.00	62.53	140		231.0	203
						50930	24440	41.00	63.02				213
0.105	0.20	0.014	0.03	0.032	1400	48380	23430	39.00	60.55	140		231.0	
						48380	23430	40.00	59.04				
0.105	0.20	0.014	0.03	0.032	1400	49400	24440	39.00	62.53	140		231.0	235
						46530	22500	42.00	63.35				
0.105	0.20	0.014	0.03	0.032	1400	48570	24540	41.00	66.64	140		231.0	
						48060	24540	39.00	65.98				
0.12	0.37	0.005	0.026	0.034	1400	49400	22410	37.00	54.29	130		214.5	233
						49400	23430	37.00	54.83				
0.12	0.37	0.005	0.026	0.034	1400	50420	23430	38.50	58.78	125		206.3	218
						50420	24440	38.50	66.37				
0.12	0.37	0.005	0.026	0.034	1400	50420	24440	39.50	60.55	120		198.0	219
						50420	23430	40.00	62.53				
0.22	0.42	0.070	0.025	0.022	1200	57550	28520	31.00	43.44	120		198.0	148
						56250	26590	35.50	56.26				159
0.24	0.39	0.093	0.038	0.037	1250	63660	34630	32.00	47.86				
						61670	31700	16.00	18.30				
					1325	61360	31700	32.50	49.37	92.5		152.6	130
						59580	30560	30.00	53.20				136
0.32	0.60	0.151	0.025	0.036	1225	71300	50930	12.50	20.42				
						73850	44820	17.00	43.44				
					1245	70280	32590	24.00	29.10	60		99.0	95.9
					1225	73850	35650	29.00	49.29				93.1
0.34	0.54	0.146	0.035	0.031	1250	69030	30680	28.00	48.23	67.5		111.4	103
						71500	34770	29.00	51.90				87.6
0.34	0.58	0.200	0.042	0.036	1250	69030	34770	22.00	33.46	62.5		103.1	96.8
						72610	35790	27.50	42.00				94.5

CHEMICAL COMPOSITION					ANNEALING HEAT IN DEGREES	TENSILE
C	MN	SI	P	S		
0.34	0.64	0.193	0.032	0.035	1270	77
						71
					1310	70
					1270	71
0.34	0.65	0.219	0.024	0.031	1325	70
						72
0.34	0.54	0.176	0.026	0.037	1255	76
						75
					1300	70
						70
0.34	0.60	0.183	0.032	0.035	1275	72
						71
0.34	0.63	0.168	0.031	0.035	1225	76
						75
0.35	0.62	0.172	0.034	0.029	1325	66
						70
0.35	0.62	0.174	0.025	0.031	1260	73
						74
					1280	71
					1290	72
0.35	0.67	0.195	0.025	0.041	1270	74
						76
					1290	75
					1310	75
					1340	71
					1350	72
0.35	0.68	0.22	0.032	0.025	1300	72
						74
0.36	0.39	0.134	0.029	0.029	1285	69
						68
0.36	0.66	0.204	0.032	0.029	1250	75
						77
					1300	74
						73
					1340	68
						68
0.386	0.64	0.200	0.040	0.032	1250	70
						70
0.45	0.63	0.182	0.034	0.023	1350	79
						79
0.45	0.69	0.226	0.028	0.039	1360	83
						86
0.46	0.61	0.148	0.028	0.024	1350	77
						85
0.47	0.67	0.373	0.032	0.032	1275	86
						91
					1450	83
					1250	84

	ANNEALING HEAT IN DEGREES	PHYSICAL PROPERTIES				STANDARD CUTTING SPEED IN FEET PER MINUTE FOR TOOLS MARKED AS NUMBERED BELOW IN FOLDER 20, TOOL NO. 1, FOLDER 21, TOOL 27 AND 26			STANDARD CUTTING SPEED AS FIGURED BY THE FORMULA
		TENSILE STRENGTH	ELASTIC LIMIT	PER CENT OF EXTENSION	PER CENT OF CONTRACTION	NO. 27	NO. 26	NO. 1 ESTIMATED	
5	1270	77920	36670	32.00	32.76				
		71300	35650	30.00	50.14				
	1310	70280	31580	28.00	42.24				89.2
	1270	71300	33610	26.00	43.74	62.5		103.1	90.1
1	1325	70280	32590	30.00	50.14	62.5		103.1	99.8
		72320	33610	31.00	47.57				97.1
7	1255	76900	40740	27.00	43.44				
		75880	38700	27.00	42.24				
	1300	70280	34630	29.00	44.34	60		99	100
		70280	33610	23.00	28.08				96.1
5	1275	72830	34630	30.00	48.73	60		99	95.5
		71300	32590	29.00	49.57				98.2
5	1225	76390	40740	30.00	44.64	57.5		94.9	90.8
		75880	38700	30.00	45.24				89.9
9	1325	69770	34630	27.00	46.40	65		107.3	100
		70790	34630	29.00	43.44				99.2
1	1260	73850	34630	30.00	42.84				
		74350	35650	27.00	41.92				
	1280	71810	35650	28.00	46.40				95.4
	1290	72830	35650	28.50	49.57	62.5		103.1	94.7
1	1270	74350	36670	25.00	49.29				
		76900	38700	25.00	33.41				
	1290	75880	39720	24.00	50.42				
	1310	75370	39720	26.00	48.73				
	1340	71530	35510	28.50	55.00				97.5
	1350	72320	35650	30.00	52.93	62.5		103.1	97.2
5	1300	72830	35650	31.00	49.86	60		99.0	96.0
		74350	36620	32.00	48.73				93.5
9	1285	69770	32590	27.00	41.31	66		108.9	106
		68750	32590	25.00	47.28				101
9	1250	75370	36160	21.00	36.63				
		77920	38200	24.50	40.39				
	1300	74350	37690	27.00	40.69				
		73350	37180	25.50	42.24				
	1340	68750	34630	26.00	42.84	65		107.3	102
		68750	34120	27.50	43.44				103
2	1250	70280	34630	28.50	43.44	70		115.5	100
		70280	34630	29.50	42.24				101
3	1350	79450	41760	28.20	42.84	55		90.8	83.5
		79960	40740	26.00	38.21				81.6
9	1360	83520	46850	25.00	42.24	45		74.3	76.5
		86070	47870	19.50	39.97				69.8
4	1350	77410	37690	27.75	49.01	50		82.5	86.3
		85520	41760	24.65	42.24				74.0
2	1275	86580	55000	8.50	11.66				
		91530	44990	19.00	28.12				
	1450	83520	42780	23.00	37.26				
	1250	84540	43800	27.00	42.24				

CHEMICAL COMPOSITION						ANNEALING HEAT IN DEGREES	PHYSICAL PROPERTIES				STANDARD FEET PER MARKED AS IN FOLDE FOLDER 21
C	MN	SI	P	S			TENSILE STRENGTH	ELASTIC LIMIT	PER CENT OF EXTENSION	PER CENT OF CONTRACTION	NO. 27
						1450	91530	55220	19.50	25.74	38
						COOLED RAPIDLY	96770	56020	21.50	28.76	
						TREAT'D	102880	68240	16.50	21.49	30
0.53	0.68	0.258	0.028	0.027		SEVER'L TIMES	102370	67230	20.00	44.04	
							108480	58060	10.50	11.66	
0.59	0.74	0.377	0.033	0.030		1100	110510	58060	16.00	24.30	
						1425	89120	43800	22.00	33.41	
						1150	93710	42780	23.00	34.38	
							101350	52960	20.00	34.05	30
						1440	101350	51440	19.00	29.44	
							123740	62380	10.00	15.37	
0.64	0.63	0.047		0.039		1050	122230	66210	5.00	5.75	
							118500	70000	14.00		
0.64	0.70	0.21	0.044								
							91670	60090	7.00	11.66	BY ACTUA
1.00	1.11	0.305	0.036	0.049			101860	53980	5.00	9.73	
					HAMMER HARDENED						
0.75	0.50	0.180	0.024	0.066	HAMMER HARDENED						
0.75	0.50	0.180	0.024	0.066	HAMMER HARDENED						
0.84	0.58	0.304	0.037	0.029	HAMMER HARDENED						
0.84	0.58	0.304	0.037	0.029	HAMMER HARDENED						
0.84	0.58	0.304	0.037	0.029	HAMMER HARDENED						
1.05	0.86	0.147	0.034	0.027	HAMMER HARDENED		105030		2.00	3.07	
							96770		2.00	3.16	
1.05	0.86	0.147	0.027	0.034	HAMMER HARDENED		102270	71590	1.00	0.75	

PER CENT OF CONTRACTION	STANDARD CUTTING SPEED IN FEET PER MINUTE FOR TOOLS MARKED AS NUMBERED BELOW IN FOLDER 20, TOOL NO. 1, FOLDER 21, TOOL 27 AND 26			STANDARD CUTTING SPEED AS FIGURED BY THE FORMULA	CHEMICAL COMPOSITION					ANNEALING HEAT IN DEGREES	PHYSICAL PROPERTIES				STANDARD CUTTING SPEED IN FEET PER MINUTE FOR TOOLS MARKED AS NUMBERED BELOW IN FOLDER 20, TOOL NO. 1, FOLDER 21, TOOL 27 AND 26	
	NO. 27	NO. 26	NO. 1 ESTIMATED		C	MN	SI	P	S		TENSILE STRENGTH	ELASTIC LIMIT	PER CENT OF EXTENSION	PER CENT OF CONTRACTION	NO. 27
32.76										1450	91530	55220	19.50	25.74	38
30.14										COOLED RAPIDLY	96770	56020	21.50	28.76	
42.24				89.2											
43.74	62.5		103.1	90.1						TREAT'D SEVER'L TIMES	102880	68240	16.50	21.49	30
50.14				99.8	0.53	0.68	0.258	0.028	0.027		102370	67230	20.00	44.04	
47.57	62.5		103.1	97.1											
43.44											108480	58060	10.50	11.66	
42.24					0.59	0.74	0.377	0.033	0.030	1100	110510	58060	16.00	24.30	
44.34				100						1425	89120	43800	22.00	33.41	
28.08	60		99	96.1						1150	93710	42780	23.00	34.38	
48.73				95.5							101350	52960	20.00	34.05	30
49.57	60		99	98.2						1440	101350	51440	19.00	29.44	
44.64				90.8							123740	62380	10.00	15.37	
45.24	57.5		94.9	89.9	0.64	0.63	0.047		0.039	1050	122230	66210	5.00	5.75	
46.40				100											
43.44	65		107.3	99.2	0.64	0.70	0.21	0.044			118500	70000	14.00		
42.84											91670	60090	7.00	11.66	BY ACTUAL
41.92					1.00	1.11	0.305	0.036	0.049		101860	53980	5.00	9.73	
46.40				95.4											
49.57	62.5		103.1	94.7											
49.29					0.75	0.50	0.180	0.024	0.066	HAMMER HARDENED					
33.41															
50.42															
48.73					0.75	0.50	0.180	0.024	0.066	HAMMER HARDENED					
55.00				97.5											
52.93	62.5		103.1	97.2											
49.86				96.0											
48.73	60		99.0	93.5	0.84	0.58	0.304	0.037	0.029	HAMMER HARDENED					
41.31				106											
47.28	66		108.9	101											
36.63															
40.39					0.84	0.58	0.304	0.037	0.029	HAMMER HARDENED					
40.60															
42.24															
42.84				102											
43.44	65		107.3	103	0.84	0.58	0.304	0.037	0.029	HAMMER HARDENED					
43.44				100											
42.24	70		115.5	101											
42.84				83.5							105930		2.00	3.97	
38.21	55		90.8	81.6	1.05	0.86	0.147	0.034	0.027	HAMMER HARDENED	96770		2.00	3.16	
42.24				76.5											
39.97	45		74.3	69.8											
49.01				86.3											
42.24	50		82.5	74.0	1.05	0.86	0.147	0.027	0.034	HAMMER HARDENED	102270	71590	1.00	0.75	
11.66															
28.12															
37.26															
42.24															

STANDARD CUTTING SPEED IN FEET PER MINUTE FOR TOOL MARKED AS NUMBERED BELOW IN FOLDER 20, TOOL NO. 1, FOLDER 21, TOOL 27 AND 26			STANDARD CUTTING SPEEDS FOR TOOL NO. 1 AS FIGURED BY THE FORMULA
NO. 27	NO 26	NO. 1 ESTIMATED	
38		62.7	64.8 62.3
30		49.5	51.5 57.6
30		49.5	58.2 57.5
	25	34	38.0
	22	30	27.0
		45.0	45.0
BY ACTUAL TEST		41.5	43.9 33.0
	15	20.4	
	12	16.3	
	19	25.8	
	15	20.4	
	12	16.3	
	15	20.4	
	15	20.4	

TABLE 142

Effect of Depth of Cut and Feed on Cutting Speed

Using our standard $1\frac{7}{8}$ inch tool (see Folder 5, Fig. 21a), standard cut 20 minutes' duration, cutting "Medium Steel" forging of chemical and physical properties as referred to on Folder 20. (See paragraph 829)

All of the cutting speeds given in this table are safe to use.

Higher cutting speeds can in all cases be used, but our experiments were not sufficiently complete to indicate how much higher.

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FROM EXPERIMENTS REDUCED TO NO. 1 TOOL ON FOLDER 20, TABLE 138	CUTTING SPEED IN FEET PER MINUTE BY FORMULA $V = \frac{11.5}{F^{.5} D^{.5}}$
$\frac{1}{8}$	$\frac{1}{4}$	67.3	75.5
$\frac{3}{16}$	$\frac{1}{8}$	82.5	83.8
	$\frac{1}{4}$	71.8	75.5
$\frac{1}{4}$	$\frac{1}{16}$	100.8	97.3
	$\frac{1}{8}$	74.3	75.5
	$\frac{1}{4}$	65.5	68.1
	$\frac{1}{2}$	47.9	53.0
$\frac{3}{8}$	$\frac{1}{8}$	47.9	59.0
	$\frac{1}{4}$	46.2	45.8
$\frac{7}{16}$	$\frac{1}{8}$	61.05	61.9
	$\frac{1}{4}$	46.2	48.1
$\frac{21}{32}$	$\frac{1}{8}$	47.0	48.1
$\frac{3}{4}$	$\frac{1}{8}$	44.6	46.0
$\frac{13}{16}$	$\frac{1}{8}$	42.1	44.6

TABLE 143

Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 18, also see paragraphs 767 to 794

STANDARD $1\frac{1}{4}$" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
3/32	1/64	518	259	118
	1/32	366	183	83.2
	1/16	257	129	58.4
	3/32	209	105	47.5
1/8	1/64	450	225	102
	1/32	317	158	72.0
	1/16	223	112	50.7
	3/32	182	90.8	41.4
	1/8	157	78.5	35.7
3/16	1/64	370	185	84.1
	1/32	260	130	59.1
	1/16	183	91.7	41.6
	3/32	149	74.6	33.8
	1/8	129	64.5	29.3
	1/16	105	52.6	23.8
1/4	1/64	322	161	73.2
	1/32	227	113	51.6
	1/16	159	79.7	36.1
	3/32	130	65.0	29.5
	1/8	112	56.1	25.5
	1/16	91.4	45.7	20.8
3/8	1/64	264	132	60.0
	1/32	186	93.1	42.3
	1/16	131	65.5	29.8
	3/32	107	53.4	24.1
	1/8	92.2	46.1	20.8
1/2	1/64	230	115	52.3
	1/32	162	80.9	36.8
	1/16	114	56.9	25.9
	3/32	92.6	46.3	21.0

TABLE 144

Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes.

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 18, also see paragraphs 767 to 794

STANDARD 1" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
3/32	1/64	490	245	111
	1/32	339	169	77.0
	1/16	235	117	53.4
	3/32	189	94.5	43.0
1/8	1/64	427	214	97.0
	1/32	296	148	67.2
	1/16	205	102	46.6
	3/32	165	83.0	37.5
	1/8	142	71.0	32.3
3/16	1/64	358	179	81.3
	1/32	247	124	56.1
	1/16	171	85.5	38.8
	3/32	138	69.0	31.3
	1/8	118	59.0	26.8
	1/16	95.0	47.5	21.6
1/4	1/64	315	157	71.6
	1/32	218	109	49.5
	1/16	150	75.0	34.1
	3/32	121	60.5	27.5
	1/8	104	52.0	23.6
3/8	1/64	263	132	59.8
	1/32	182	91.0	41.4
	1/16	126	62.8	28.5
	3/32	101	50.6	23.0
1/2	1/64	232	116	52.7
	1/32	161	80.5	36.6
	1/16	111	55.7	25.3

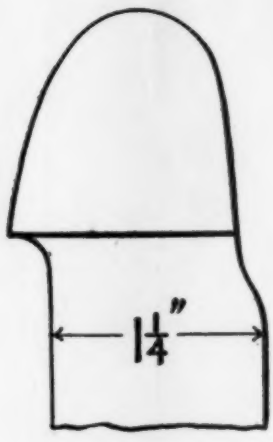


TABLE 149

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraph 751. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814

STANDARD $1\frac{1}{4}$" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	239	119.6	69.8
	1/32	191	95.3	55.6
	1/16	142	70.8	41.3
	3/32	118	59.1	34.4
	1/8	103	51.7	30.2
	1/16	85.0	42.5	24.8
1/8	1/64	216	108	63.1
	1/32	172	86.2	50.3
	1/16	128	64.0	37.3
	3/32	107	53.4	31.2
	1/8	93.4	46.7	27.3
	1/16	76.8	38.4	22.4
3/16	1/64	187	93.5	54.6
	1/32	149	74.6	43.6
	1/16	111	55.5	32.7
	3/32	92.5	46.3	27.0
	1/8	73.1	36.5	21.3
	1/16	66.4	33.2	19.4
1/4	1/64	168	84.1	49.1
	1/32	134	67.2	39.2
	1/16	99.8	49.9	29.1
	3/32	83.2	41.6	24.3
	1/8	72.6	36.3	21.2
	1/16	59.7	29.8	17.4
3/8	1/64	144	71.8	41.9
	1/32	115	57.3	33.4
	1/16	85.1	42.6	24.8
	3/32	70.9	35.5	20.7
	1/8	62.0	31.0	18.1
	1/16	51.0	25.5	14.9
1/2	1/64	131	55.6	38.3
	1/32	105	52.3	30.5
	1/16	77.6	38.8	22.7
	3/32	64.7	32.4	18.9
	1/8	56.6	28.3	16.5
	1/16	46.5	23.3	13.6
3/4	1/64	112	56.0	32.7
	1/32	89.2	44.6	26.0
	1/16	66.2	33.1	19.3
	3/32	55.2	27.6	16.1
	1/8	48.3	24.2	14.1
	1/16	39.7	19.8	11.6

TABLE 150

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraph 751. Tools to be reground 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814

STANDARD 1" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	226	113	66.0
	1/32	177	88.4	51.6
	1/16	130	64.8	37.8
	3/32	107	53.5	31.2
	1/8	92.8	46.4	27.1
	1/16	75.7	37.8	22.1
1/8	1/64	205	102	59.8
	1/32	160	85.1	46.8
	1/16	118	58.8	34.3
	3/32	97.0	48.5	23.3
	1/8	84.2	42.1	24.6
	1/16	68.6	34.3	20.0
3/16	1/64	181	90.6	52.9
	1/32	142	70.8	41.3
	1/16	104	51.9	30.3
	3/32	85.8	42.9	25.0
	1/8	74.3	37.2	21.7
	1/16	60.6	30.3	17.7
1/4	1/64	165	82.3	48.1
	1/32	129	64.4	37.5
	1/16	94.3	47.1	27.5
	3/32	77.8	38.9	22.7
	1/8	67.5	33.7	19.7
	1/16	55.0	27.5	16.1
3/8	1/64	143	71.5	41.8
	1/32	112	56.0	32.6
	1/16	81.9	41.0	23.9
	3/32	67.6	33.8	19.7
	1/8	58.6	29.3	17.1
	1/16	57.5	28.7	16.8
1/2	1/64	132	66.2	38.6
	1/32	104	51.6	30.2
	1/16	75.8	37.9	22.1
	3/32	62.6	31.3	18.3
	1/8	54.2	27.1	15.8
	1/16	44.2	22.1	12.9

VOLUME TIGHTLY BOUND

TABLE 145

Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 18, also see paragraphs 767 to 794

STANDARD $\frac{7''}{8}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
3/32	1/64	476	238	108
	1/32	325	162	73.8
	1/16	222	111	50.4
	3/32	177	88.4	40.2
1/8	1/64	420	210	95.5
	1/32	286	143	65.0
	1/16	195	97.6	44.4
	3/32	156	77.9	35.4
	1/8	133	66.4	30.2
3/16	1/64	352	176	80.0
	1/32	240	120	54.5
	1/16	164	82	37.3
	3/32	131	65.5	29.8
	1/8	112	56.0	25.5
1/4	1/64	312	156	70.9
	1/32	213	107	48.4
	1/16	145	72.6	33.0
	3/32	116	58.1	26.4
3/8	1/64	264	132	60.0
	1/32	180	90.2	41.0
	1/16	122	61.1	27.8
1/2	1/64	237	118	53.8
	1/32	162	80.8	36.7

TABLE 146

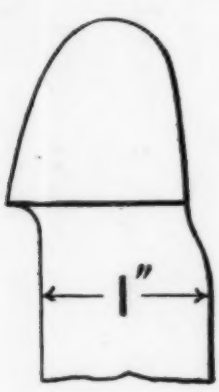
Practical Table of Cutting Speeds

Corresponding to different depths of cut and thickness
Soft, Medium and Hard Steel, when best modern high-
are used of steel like tool No. 1, Folder 20, Table. 138.
graphs 743 to 747. Tools to be reground every 1 hour a
utes.

For accurate laws and formulæ representing the eff
and depth of cut on cutting speed, see Folder 18, als
graphs 767 to 794

STANDARD $\frac{3''}{4}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MIN TOOL WHICH IS TO LAST 1 HOU MINUTES BEFORE REGRINDING	
		SOFT STEEL	MEDIUM STEEL
3/32	1/64	482	241
	1/32	323	161
	1/16	217	108
	3/32	172	85.8
1/8	1/64	423	212
	1/32	284	142
	1/16	190	95.2
	3/32	151	75.3
	1/8	128	63.8
3/16	1/64	358	179
	1/32	240	120
	1/16	161	80.5
	3/32	127	63.7
1/4	1/64	320	160
	1/32	215	107
	1/16	144	72
3/8	1/64	276	138
	1/32	185	92.4



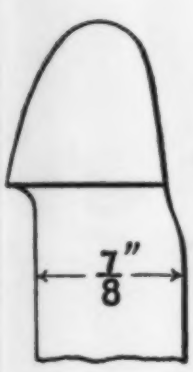


TABLE 151

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraph 751. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814.

STANDARD $\frac{7''}{8}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	220	110	64.2
	1/32	169	84.6	49.4
	1/16	122	61.2	35.7
	3/32	99.8	49.9	29.1
	1/8	86.4	43.2	25.2
	1/16	70.1	35.1	20.5
1/8	1/64	202	101	58.9
	1/32	156	77.8	45.4
	1/16	112	56.2	32.8
	3/32	91.8	45.9	26.8
	1/8	79.3	39.7	23.2
	1/16	64.3	32.2	18.8
3/16	1/64	178	89.0	52.0
	1/32	137	68.6	40.1
	1/16	99.4	49.7	29.0
	3/32	81.0	40.5	23.7
	1/8	70.1	35.0	20.5
	1/16	56.8	28.4	16.6
1/4	1/64	163	81.5	47.7
	1/32	126	62.9	36.7
	1/16	90.8	45.4	26.5
	3/32	74.1	37.0	21.6
	1/8	64.1	32.0	18.7
	1/16	52.0	26.0	15.2
3/8	1/64	144	71.8	41.9
	1/32	111	55.4	32.3
	1/16	80.0	40.0	23.4
	3/32	65.3	32.6	19.1
	1/8	56.4	28.2	16.5
	1/16	45.8	22.9	13.4
1/2	1/64	135	67.5	39.4
	1/32	104	52.1	30.4
	1/16	75.2	37.6	22.0
	3/32	61.4	30.7	17.9
	1/8	43.1	21.6	12.6

TABLE 152

Practical Table of Cutting Spee Cast Iron

Corresponding to different depths of cut and thickness o
on Soft, Medium and Hard Cast Iron, when best modern
speed tools are used of steel like tool No. 1, Folder 20,
138. See paragraphs 751. Tools to be reground every 1
and 30 minutes

For accurate laws and formulæ representing the effe
feed and depth of cut on cutting speed, see Folder 19, al
paragraphs 795 to 814

STANDARD $\frac{3''}{4}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED, IN FEET PER M UTE FOR A TOOL WHICH IS LAST 1 HOUR AND 30 MINU BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD C IRON
3/32	1/64	222	111	65.
	1/32	169	84.3	49.
	1/16	120	59.8	34.
	3/32	97.0	48.5	28.
	1/8	83.4	41.7	24.
	1/16	66.4	33.2	19.
1/8	1/64	203	102	59.
	1/32	156	78.2	45.
	1/16	110	55.0	32.
	3/32	88.8	44.4	25.
	1/8	76.2	38.1	22.
	1/16	60.9	30.4	17.
3/16	1/64	181	90.6	52.
	1/32	137	68.5	40.
	1/16	97.7	48.9	28.
	3/32	78.0	39.0	22.
	1/8	67.5	33.7	19.
	1/16	54.2	27.1	15.
1/4	1/64	167	83.6	48.
	1/32	126	63.2	36.
	1/16	90.8	45.4	26.
	3/32	72.7	36.3	21.
	1/8	62.7	31.3	18.
3/8	1/64	150	75.0	43.
	1/32	113	56.7	33.
	1/16	81.0	40.5	23.
	3/32	65.5	32.7	19.

TABLE 145

Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 18, also see paragraphs 767 to 794

STANDARD $\frac{7''}{8}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
3/32	1/64	476	238	108
	1/32	325	162	73.8
	1/16	222	111	50.4
	3/32	177	88.4	40.2
1/8	1/64	420	210	95.5
	1/32	286	143	65.0
	1/16	195	97.6	44.4
	3/32	156	77.9	35.4
	1/8	133	66.4	30.2
3/16	1/64	352	176	80.0
	1/32	240	120	54.5
	1/16	164	82	37.3
	3/32	131	65.5	29.8
	1/8	112	56.0	25.5
1/4	1/64	312	156	70.9
	1/32	213	107	48.4
	1/16	145	72.6	33.0
	3/32	116	58.1	26.4
3/8	1/64	264	132	60.0
	1/32	180	90.2	41.0
	1/16	122	61.1	27.8
1/2	1/64	237	118	53.8
	1/32	162	80.8	36.7

TABLE 146

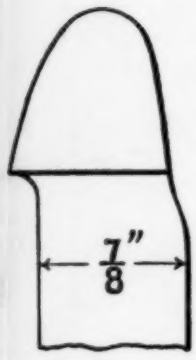
Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table. 138. See paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes.

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 18, also see paragraphs 767 to 794

STANDARD $\frac{3''}{4}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
3/32	1/64	482	241	110
	1/32	323	161	73.4
	1/16	217	108	49.3
	3/32	172	85.8	39.0
1/8	1/64	423	212	96.1
	1/32	284	142	64.5
	1/16	190	95.2	43.2
	3/32	151	75.3	34.2
	1/8	128	63.8	29.0
3/16	1/64	358	179	81.4
	1/32	240	120	54.5
	1/16	161	80.5	36.6
	3/32	127	63.7	28.7
1/4	1/64	320	160	72.7
	1/32	215	107	48.8
	1/16	144	72	32.7
3/8	1/64	276	138	62.7
	1/32	185	92.4	42.0



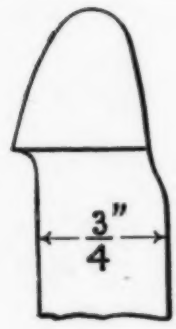


TABLE 151

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraph 751. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814.

STANDARD $\frac{7''}{8}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	220	110	64.2
	1/32	169	84.6	49.4
	1/16	122	61.2	35.7
	3/32	99.8	49.9	29.1
	1/8	86.4	43.2	25.2
	1/16	70.1	35.1	20.5
1/8	1/64	202	101	58.9
	1/32	156	77.8	45.4
	1/16	112	56.2	32.8
	3/32	91.8	45.9	26.8
	1/8	79.3	39.7	23.2
	3/16	64.3	32.2	18.8
3/16	1/64	178	89.0	52.0
	1/32	137	68.6	40.1
	1/16	99.4	49.7	29.0
	3/32	81.0	40.5	23.7
	1/8	70.1	35.0	20.5
	3/16	56.8	28.4	16.6
1/4	1/64	163	81.5	47.7
	1/32	126	62.9	36.7
	1/16	90.8	45.4	26.5
	3/32	74.1	37.0	21.6
	1/8	64.1	32.0	18.7
	3/16	52.0	26.0	15.2
3/8	1/64	144	71.8	41.9
	1/32	111	55.4	32.3
	1/16	80.0	40.0	23.4
	3/32	65.3	32.6	19.1
	1/8	56.4	28.2	16.5
	3/16	45.8	22.9	13.4
1/2	1/64	135	67.5	39.4
	1/32	104	52.1	30.4
	1/16	75.2	37.6	22.0
	3/32	61.4	30.7	17.9
	1/8	43.1	21.6	12.6

TABLE 152

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraphs 751. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814

STANDARD $\frac{3''}{4}$ TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED, IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	222	111	65.0
	1/32	169	84.3	49.2
	1/16	120	59.8	34.9
	3/32	97.0	48.5	28.3
	1/8	83.4	41.7	24.4
	3/16	66.4	33.2	19.4
1/8	1/64	203	102	59.3
	1/32	156	78.2	45.6
	1/16	110	55.0	32.0
	3/32	88.8	44.4	25.9
	1/8	76.2	38.1	22.3
	3/16	60.9	30.4	17.8
3/16	1/64	181	90.6	52.9
	1/32	137	68.5	40.0
	1/16	97.7	48.9	28.5
	3/32	78.0	39.0	22.8
	1/8	67.5	33.7	19.7
	3/16	54.2	27.1	15.8
1/4	1/64	167	83.6	48.8
	1/32	126	63.2	36.9
	1/16	90.8	45.4	26.3
	3/32	72.7	36.3	21.2
	1/8	62.7	31.3	18.3
3/8	1/64	150	75.0	43.8
	1/32	113	56.7	33.1
	1/16	81.0	40.5	23.6
	3/32	65.5	32.7	19.1

TABLE 147

Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table 138, see paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 18, also see paragraphs 767 to 794

STANDARD $\frac{5}{8}$" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
1/16	1/64	548	274	125
	1/32	358	179	81.6
	1/16	235	117	53.3
3/32	1/64	467	234	106
	1/32	306	153	69.5
	1/16	200	100	45.5
	3/32	156	78.0	35.5
1/8	1/64	417	209	94.8
	1/32	273	136	62.0
	1/16	179	89.3	40.6
	3/32	140	69.8	31.7
3/16	1/64	362	181	82.2
	1/32	236	118	53.8
	1/16	155	77.4	35.2
1/4	1/64	328	164	74.5
	1/32	215	107	48.8
3/8	1/64	286	143	65.0

TABLE 148

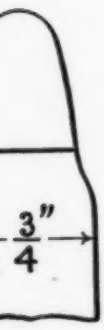
Practical Table of Cutting Speeds, Steel

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Steel, when best modern high-speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraphs 743 to 747. Tools to be reground every 1 hour and 30 minutes.

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed see Folder 18, also see paragraphs 767 to 794

STANDARD $\frac{1}{2}$" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT STEEL	MEDIUM STEEL	HARD STEEL
1/16	1/64	510	255	116
	1/32	322	161	73.2
	1/16	203	102	46.2
3/32	1/64	445	223	101
	1/32	281	141	63.9
	1/16	177	88.7	40.2
	3/32	135	67.4	30.7
1/8	1/64	404	202	91.8
	1/32	255	128	57.9
	1/16	161	81	36.6
3/16	1/64	359	179	81.6
	1/32	226	113	51.4
1/4	1/64	330	165	25.0



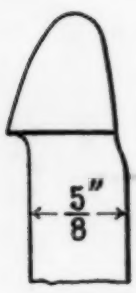


TABLE 153

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraph 751. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814

STANDARD $\frac{5}{8}$" TOOL

DEPTH OF CUT IN INCHES	FEED IN INCHES	CUTTING SPEED, IN FEET PER MINUTE FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	216	108	63.0
	1/32	160	80.0	46.6
	1/16	110	55.0	32.2
	3/32	88.4	44.2	25.8
	1/8	75.4	37.7	22.0
1/8	1/64	200	100	58.6
	1/32	148	74.0	43.3
	1/16	104	51.8	30.2
	3/32	82.6	41.3	24.1
	1/8	69.6	34.8	20.3
3/16	1/64	183	91.6	68.0
	1/32	135	67.5	39.4
	1/16	94.0	47.0	27.4
	3/32	75.4	37.7	22.0
	1/8	64.3	32.2	18.8
1/4	1/64	171	85.7	50.1
	1/32	126	63.2	36.9
	1/16	87.8	43.9	25.6
	3/32	70.4	35.2	20.6
3/8	1/64	156	77.8	45.4
	1/32	116	57.8	33.8
	1/16	79.7	39.9	23.3

TABLE 154

Practical Table of Cutting Speeds Cast Iron

Corresponding to different depths of cut and thickness of feed on Soft, Medium and Hard Cast Iron, when best modern high speed tools are used of steel like tool No. 1, Folder 20, Table 138. See paragraph 751. Tools to be reground every 1 hour and 30 minutes

For accurate laws and formulæ representing the effect of feed and depth of cut on cutting speed, see Folder 19, also see paragraphs 795 to 814

STANDARD $\frac{1}{2}$" TOOL

DEPTH OF CUT INCHES	FEED IN INCHES	CUTTING SPEED, IN FEET PER MINUTE, FOR A TOOL WHICH IS TO LAST 1 HOUR AND 30 MINUTES BEFORE REGRINDING		
		SOFT CAST IRON	MEDIUM CAST IRON	HARD CAST IRON
3/32	1/64	206	103	60.0
	1/32	147	73.3	42.8
	1/16	97.5	48.8	28.5
	3/32	76.0	38.0	22.2
	1/8	64.1	32.1	18.7
1/8	1/64	194	97.0	56.7
	1/32	138	69.3	40.4
	1/16	93.1	46.5	27.2
	3/32	72.1	36.1	21.3
	1/8	41.8	20.9	12.2
3/16	1/64	182	91.0	53.0
	1/32	128	64.0	37.7
	1/16	86.1	43.1	25.1
	3/32	67.4	33.7	19.6
1/4	1/64	173	86.3	50.4
	1/32	122	61.0	35.7
	1/16	81.9	41.0	23.9